The Colour and Stereo Surface Imaging System (CaSSIS) for ESA's ExoMars Trace Gas Orbiter

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Zusammenfassung: Die CaSSIS genannte Kamera (für Colour and Stereo Surface Imaging System) wurde kürzlich an Board des ExoMars Satelliten 'Trace Gas Orbiter' (TGO) von der Europäischen Raumfahrtagentur Richtung Mars gestartet. Dort wird TGO im Oktober 2016 ankommen. Die eigentliche wissenschaftliche Mission beginnt im Juni 2017. CaSSIS kann nicht nur hochauflösende Aufnahmen von der Marsoberfläche in vier verschiedenen Farben machen. Der spezielle Rotationsmechanismus erlaubt es ausserdem Stereo-Bilder anzufertigen, wobei die entspreche Region dafür nur einmal überflogen werden muss.

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1 Introduction

The Colour and Stereo Surface Imaging System (CaSSIS) is a moderately high resolution imaging system specifically designed to fly on the European Space Agency's ExoMars Trace Gas Orbiter (TGO) (VAGO et al. 2015; THOMAS et al. 2016a). The spacecraft was launched successfully from Baikonur on 14 March 2016 at 09:31 UT on a PROTON provided by the Russian space agency, ROSCOSMOS. At the time of writing, TGO is in the inter-planetary cruise and will encounter Mars on 19 October 2016. CaSSIS is the only imager onboard and has been designed to both complement the other payload elements and to provide new observations of the surface of Mars once TGO reaches its final orbit in June 2017. The paper presents a brief overview of the instrument and serves as an introduction to a more detailed paper that is currently in preparation for submission to Planetary and Space Sciences (THOMAS et al. 2016b). In view of the nature of the conference, we will particularly draw attention to the stereoscopic properties of the instrument.

2 Aims and Objectives

In the 1990s, the European Space Agency (ESA) set up a series of study teams to establish the scientific aims and objectives for a mission focussed on the search for past or present extra-terrestrial life. Outputs from these studies included a detailed report (ESA 1999) and associated papers (e.g. BRACK et al. 1999). This work eventually led to the setting up of the ExoMars mission as part of ESA's optional programme which was aimed at performing an in situ search for extinct or extant life on Mars. During the initial development, it became clear that a two-step programme was needed to guarantee adequate data return. The first element, an orbiter, was to be followed by a rover, 26 months later. The orbiter element was to provide communications while the rover was specifically targeted at investigating the sub-surface where primitive lifeforms might have survived having been protected from the harmful UV radiation present at the surface.
Although the orbiter was primarily foreseen as communication infrastructure for the rover element, the possibility to place payload on the orbiter was attractive and the detection of methane in the atmosphere of Mars (FORMISANO et al. 2004; MUMMA et al. 2009) led to the concept of providing the orbiter with the capability to detect trace gases. The instrument definition team report (ZUREK et al. 2009) suggested provision of very high spatial resolution imaging or mapping instruments (e.g., cameras and multi-beam active lasers) to provide geological context and location of small-area sources of trace gases should they exist (e.g., a volcanic vent, rift or crater). The definition team focused on a high-resolution colour stereo camera concept expanding upon the successful HRSC experiment on Mars Express (NEUKUM et al. 2004) that would provide geologic characterization.
Following various re-configurations of the ExoMars programme, the ExoMars Trace Gas Orbiter (TGO) was finally approved with a payload of 4 instruments and an entry, descent, and landing demonstrator (subsequently called Schiaparelli). Schiaparelli was also to be equipped with sensors for measuring atmospheric parameters during its descent. The final orbiter payload comprised two spectrometers (NOMAD and ACS) designed to detect trace gases, a neutron

spectrometer (FREND) to investigate water in the first metre of the surface layer, and an imaging system (CaSSIS) to provide geological context.

The main scientific objectives of CaSSIS were defined as

- to characterize sites which have been identified as potential sources of trace gases
- to investigate dynamic surface processes (e.g. sublimation, erosional processes, volcanism) which may contribute to the atmospheric gas inventory and
- to certify potential future landing sites by characterizing local slopes, rocks, and other potential hazards.

Given the limited mass and volume available, the technical solution selected emphasized colour and stereo capability with a moderately high resolution and not attempting to reach the remarkable high resolution imagery (0.25 m/px) of the HiRISE instrument on NASA's Mars Reconnaissance Orbiter (MCEWEN et al. 2007). The top level technical requirements are shown in Table 1 and were required to be obtained from a circular orbit 400 km above the Martian surface. The prime mission is to last 1 Mars year. Additional science is expected to come from the fact that TGO will not be placed in a Sun-synchronous orbit (unlike most of its predecessors) and hence diurnal variations (e.g. in surface frost coverage) also form major scientific objectives.

Tab. 1: Basic technical requirements for CaSSIS

Spatial resolution	<5 m/px
Number of colour channels	4
Swath width	>8km in full colour
Swath length	>30 km
Stereo capability	Yes, on one pass
Digital resolution	14 bit

A consortium was put together to build the instrument comprising the University of Bern as instrument development lead with support from the Astronomical Observatory in Padova and the Space Research Centre in Warsaw. Local industries were used for specific hardware elements and additional support from SGF in Hungary and the University of Arizona was also provided.

3 Instrument Concept

3.1 Functional Units

CaSSIS comprises two units (Fig. 1) – the Camera Rotation Unit (CRU) and the Electronics Unit (ELU). The CRU includes the optics (telescope) and the detector but also includes a rotation mechanism which will be used to generate the stereo pair. The ELU contains electronics boards in the form of modules for controlling the instrument activities.

3.2 Detector sub-system

The detector sub-system was based around the hybrid silicon CMOS device called Osprey from Raytheon. This 2k x 2k 10 micron pixel pitch device allows rapid read-out from 6 arbitrarily defined areas of the detector. The CaSSIS detector is a flight spare of the detector assembly to be flown in the SIMBIO-SYS experiment slated to fly on ESA's BepiColombo mission in 2018

(FLAMINI et al. 2010). The approach for CaSSIS was to use this device to produce 2048 × 256 images of the surface with sufficient rapidity so that they overlap on the ground-track. This approach is sometimes referred to as "push-frame". The advantage of this approach is that jitter can be determined easily by co-registration of the frames. However, the read-out speed constrains the best resolution one can obtain. Detailed signal to noise calculations in combination with the known properties of the detector led to a target spatial scale of around 4.6 m/px from the nominal 400 km circular orbit intended for TGO.

The timing and the internal buffering of the instrument is sufficient to allow exposure sequences of 40 "framelets" in one pass over a target. Considering the overlap needed to ensure accurate co-registration of the framelets, this results in a maximum swath length of about 40 km. The swath width is around 9.5 km.

The digital resolution of the detector is 14 bit and on ground calibration currently indicates that the device is stable and linear at the framing rates and exposure times required for CaSSIS. A radiator has been mounted to the detector system to cool the device. A heater has also been implemented. This allows us to stabilize the temperature at a value of our choice. The best option seems to be around 0°C when dark current is almost negligible for the millisecond exposure times to be used.

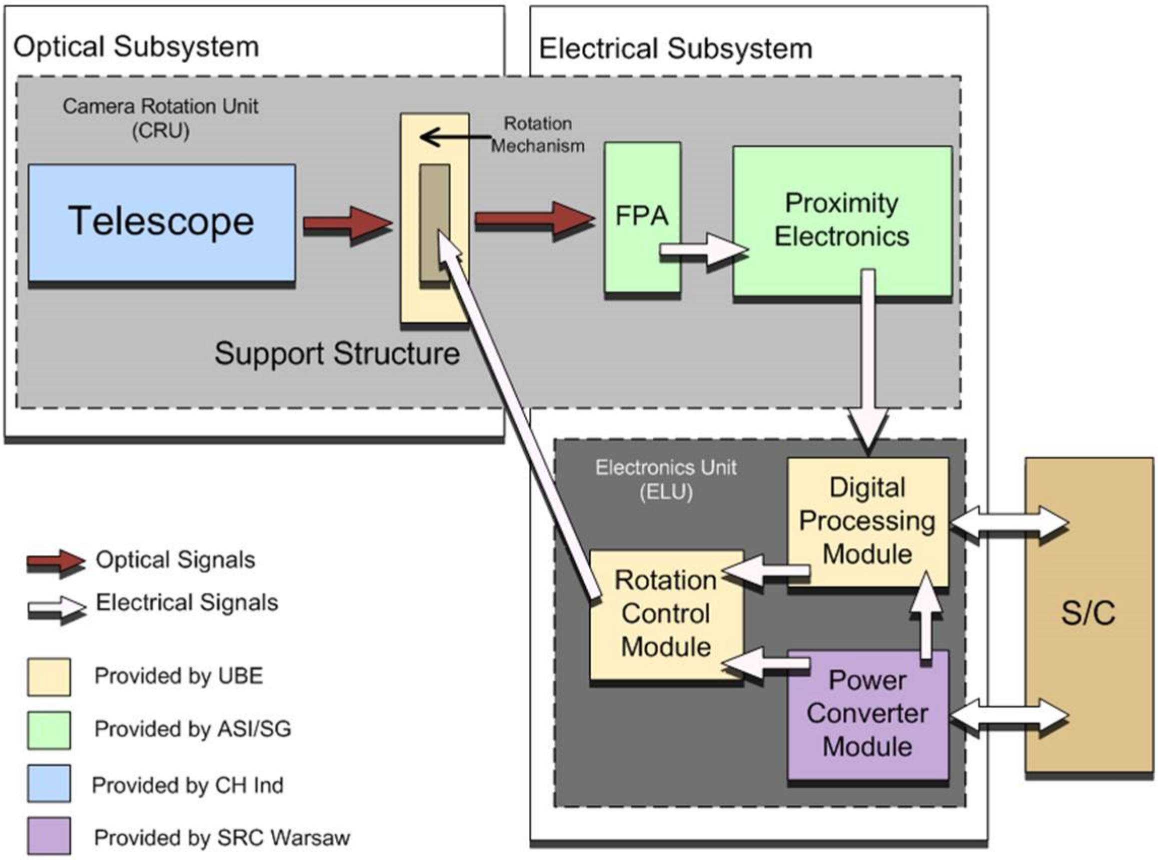

Fig. 1: Functional block diagram of the CaSSIS system.

3.3 Filter sub-system

Individual filters can be placed directly above the detector surface so that different sections of the detector provide different colour response. Custom-designed filters were deposited onto a fused silica substrate to provide 4 different bandwidths. The substrate was then mounted into the detector module. Gaps between the filters were blackened to reduce stray light and cross-talk between the different filter images. The nominal bandwidths are given in Table 2. The NIR is a long-pass filter and the bandwidth limiting is effectively provided by the detector cut-off at 1100°nm which is a consequence of the steep drop in the absorption coefficient of silicon at this wavelength. The timing and data transfer rates are such that only 3 of the 4 filter images can be obtained for each swath if full resolution and full swath width are required. Reduction of swath width and binning of each filter individually is possible providing a significant degree of operational flexibility despite this limitation.

Tab. 2: Filters implemented in CaSSIS

Filter name	Filter type	Central wavelength or cut-on wavelength [nm]
BLU	Bandpass	480
PAN	Bandpass	676
RED	Bandpass	839
NIR	Longpass	860

The capability of CaSSIS to distinguish between specific minerals on the surface of Mars has the subject of a preliminary investigation by TORNABENE et al. (2016).

3.4 Telescope sub-system

To reach the necessary image scale, an 880 mm focal length, F/6.5 telescope was designed using a carbon-fibre reinforced plastic (CFRP) structure and a three-mirror anastigmatic concept based around Zerodur™ mirrors. A fourth mirror was included primarily as a fold mirror but was also required to be powered to compensate for other constraints. The telescope design provides a small (~1%) but non-negligible geometric distortion. The optimum focus position was found in the laboratory using interferometric techniques. The mounting of the focal plane was however slightly shifted to pre-compensate the expected shrinkage of the CFRP structure caused by moisture release.

3.5 Stereo approach

The key concept of the CaSSIS system is that it uses a rotation mechanism to produce the stereo pair. The telescope in this case is not nadir-pointing but at an angle of 10° with respect to nadir. Initially, the telescope is rotated so that it points 10° in front of the nadir position on the ground-track. After acquisition of the first image, the telescope is rotated through 180° so that it now points 10° aft. The second image is then acquired. The off-nadir angle leads to an almost negligible decrease in resolution.

The idea of rotating or tilting a camera to obtain a stereo pair from one pass over an object is not new. For example, the LANYARD system from 1963 (part of the first generation of U.S. photo-reconnaissance satellites) was programmed to tilt between fore and aft to cover the same land area twice during a photographic pass and thus to acquire stereo coverage at 2 m resolution from around 160 km altitude (see http://www.fas.org/spp/military/program/imint/corona.htm and http://www.earsel.org/SIG/3D/Dati/Porto/Jacobsen1.pdf). One of the most recent implementations of this technique can be seen in the GeoEye-1 programme (see https://dg-cms-uploads-production.s3.amazonaws.com/uploads/document/file/97/DG_GeoEye1.pdf; retrieved 22 March 2016).

In addition to simplifying the optical solution and allowing a higher resolution, the rotation also neatly solves a further issue. TGO was designed such that one side (the –Y panel) is always nadir pointing. However, the spacecraft rotates about this vector in order to maintain sunlight orthogonal to the spacecraft solar panels. The CaSSIS concept follows an original idea described in MCEWEN et al. (2011) and is an elegant solution to the dual problem of the rotation of the platform about the nadir vector plus the requirement for stereoscopic imaging. Here it is the instrument that moves and not the whole spacecraft (as in the case of GeoEye-1) and, by allowing any rotation position, accomplishes not only the stereoscopic objective but also the compensation for the spacecraft attitude.

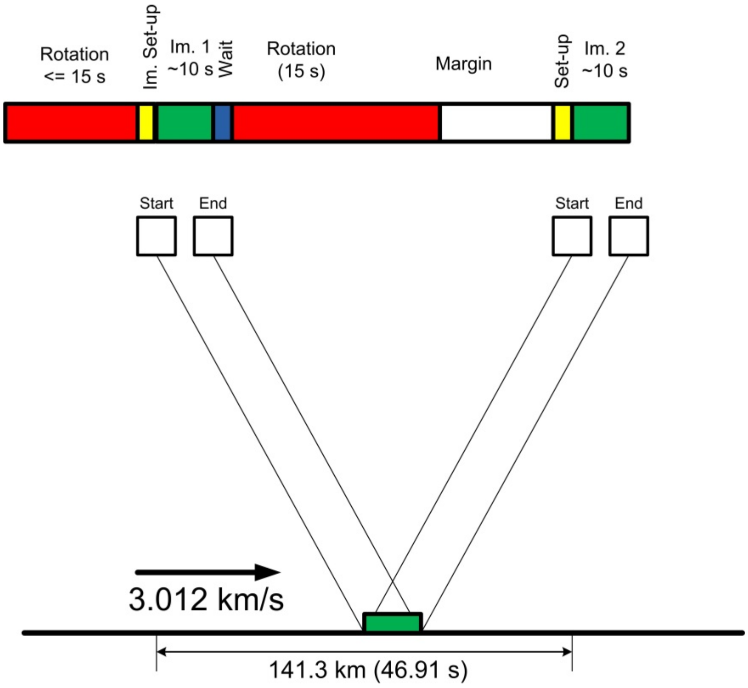

Fig. 2: Timing diagram for the stereo acquisition approach of CaSSIS.

The timing of the stereo acquisition from the 400 km nominal circular orbit is shown in Figure 2. The second image is started 46.91 s after the first which allows more than 30 s for the rotation to be achieved. When combined with the spherical shape of Mars, the resulting stereo convergence angle is nominally 22.4°. On-ground testing suggests that the convergence angle will be slightly smaller although this remains to be confirmed by observations of standard stars in flight.

3.6 Structural concept

A complexity introduced by the rotation is the need to ensure proper routing of the cables needed to drive the electronics. A cable management system (referred to as the "twist capsule") which ensures that the wiring for the detector and proximity electronics do not snag was therefore introduced. The instrument structure was then based around a T-like structure with the optics and focal plane assembly on one side of a main support element, the focal plane electronics in the centre, and the cable management system on the other side of the support. The items balance across the support which also contains the rotation mechanism necessary to align the detector and its filters with respect to the ground-track motion of the spacecraft. This neat arrangement is lightweight although care has to be taken to ensure that the structure is sufficiently stiff so that nodding provoked by vibration during launch is controlled. AlBeMet was the material chosen to give the structural support sufficient rigidity.

The CRU was decoupled from the spacecraft bench using a honeycomb panel. This improved mechanical stability as well as allowing the instrument to control its temperature rather precisely using heaters without having to be concerned with heat leaking from/to the spacecraft. The entire structure was wrapped in multi-layer insulation to reduce losses.

3.7 Rotation mechanism

The rotation mechanism consists of a hollow shaft supported by two ceramic bearings and driven by a worm gear, whereby the worm wheel is integral part of the hollow shaft. The reduction ratio is around 200:1.

High-strength titanium alloys are used for the gear component, which are hard coated to provide durability. The housing is made of AlBeMet. A stepper motor (modified Portescap P430) is connected to the worm shaft via a bellow coupling. End switches are used for zeroing; backlash is compensated by software and is calibrated in-flight. The current estimate is that positioning of the mechanism is accurate to about 0.1 deg. The current system rotates the telescope through 180 degrees in <16 s – nearly a factor of 2 faster than required.

3.8 Electronics unit (ELU)

The ELU has three main functions. Firstly, the power converter module (PCM) takes the spacecraft provided 28 V and splits this into the various voltages required by the sub-systems using appropriate DC/DC converters. The digital processing module (DPM) using a radiation-hard LEON-3 processor to control the instrument function. It is also responsible for telecommand and telemetry processing. The rotation control module (RCM) controls the mechanism and its logic.

The flight software (FSW) has been developed with simplicity in mind. On boot, the FSW takes thermal control of the instrument and ensures that all elements (and specifically the detector and telescope) reach their nominal operating temperatures. The FSW also receives and decodes telecommands, drives the detector in a master/slave configuration, and prepares the data received from the detector and proximity electronics for delivery across a SpaceWire interface to the spacecraft. Housekeeping (HK) values are also collected to monitor instrument health. A 1553 interface provides regular HK information to ground via the spacecraft.

CaSSIS can time image acquisition to an accuracy of about 1 ms which corresponds to <1 px on the ground-track implying that the size of the overlap between framelets can be maintained and/or modified accurately. The instrument timing has been verified pre-launch using stroboscopic testing.

The instrument has been allocated a data volume of 2.9 Gb/day during the prime mission. A JPEG2000 compressor is planned to be uploaded to the instrument in flight to provide data compression ratios of 3-10 depending upon the required fidelity. Typically this would result in about 6 stereo pairs per Earth day being returned together with 6-10 individual images (non-stereo) from other targets.

4 Conclusion and future work

4.1 Experimental

The complete instrument (without MLI) is shown in Figure 3. It was successfully mounted on the TGO spacecraft on 11 November 2015 and, following a series of communication tests with the spacecraft, was launched on 14 March 2016. The spacecraft is currently in interplanetary cruise. On ground testing appears to confirm that the instrument build has met its requirements and analysis of the calibration dataset acquired prior to delivery is on-going with publication intended for later this year.

4.2 Geometric analyses

A key part of the in-flight testing will be the verification of the geometric distortion. This will be investigated using standard star fields. The aim is to establish a distortion map based on the high precision astrometry provided by Hipparcos and Gaia. Images of Mars will then be inverted to eliminate the distortion. Once this has been done, co-registration of the overlapping areas in the push-frame sequence will be performed to generate final images around 9.5 km x 40 km in dimension. The stereo pairs can then be matched to provide the 3D topography of specific targets. A key element will be the development of tools for digital terrain model production.

4.3 Target selection

A target database is being constructed for CaSSIS to address the scientific goals of the experiment and the mission. It is intended eventually to open this to the public. The data rate expected and the targeting should result in ~3% of the Martian surface being studied at <5 m/px in colour and stereo every Mars year.

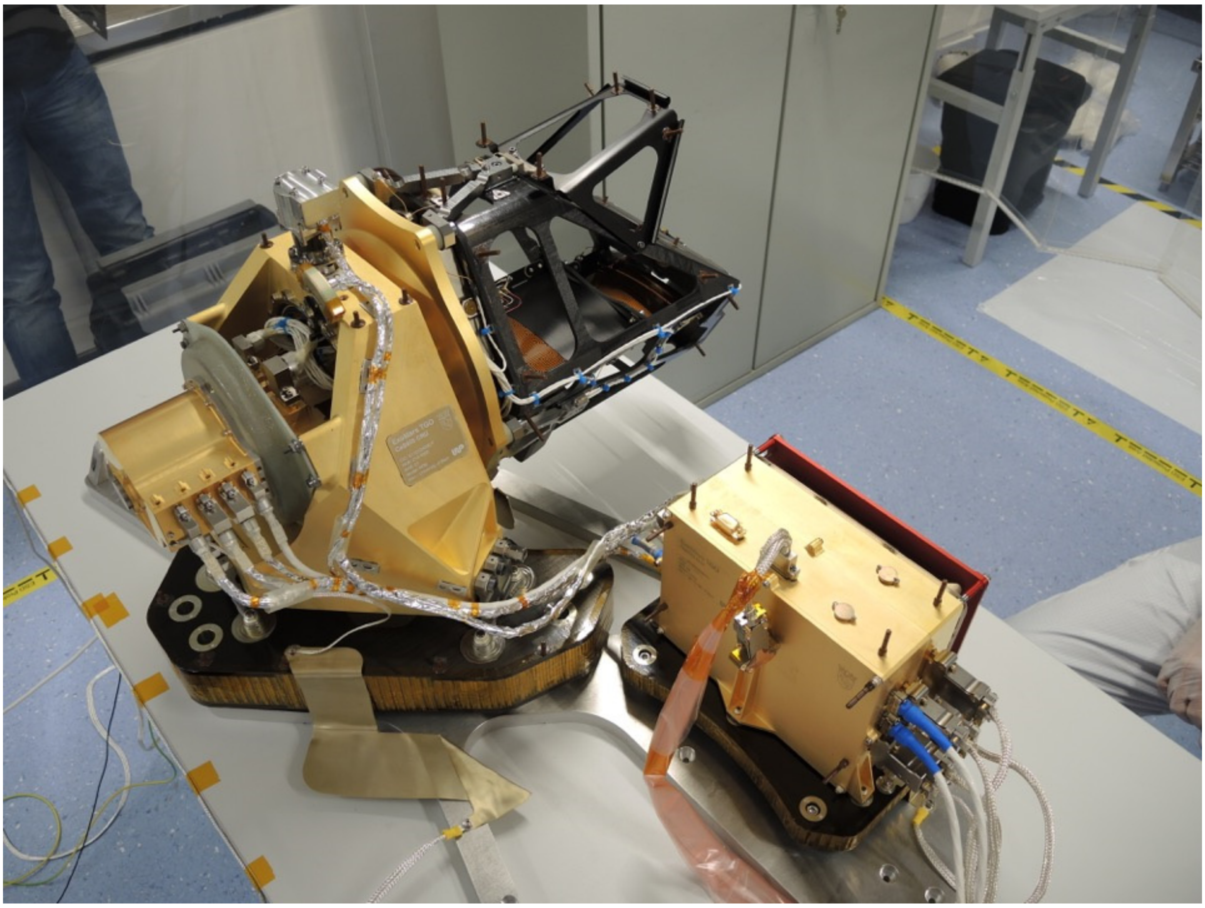

Fig. 3: The CaSSIS instrument on the bench at the University of Bern. The CRU is to the left, the ELU to the right. The black structure on the right of the CRU is the telescope. The multi-layer insulation is not mounted.

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