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TWENTY MONTHS DEVELOPMENT FOR THE CASSIS TELESCOPE: RE-USE BUILDING BLOCKS AND CONCURRENT ENGINEERING

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I. INTRODUCTION

On board of the ExoMars Trace Gas Orbiter (TGO), the Colour and Stereo Surface Imaging System (CaSSIS) developed under the lead of University of Bern, has the mission to provide stereo images of the planet's surface in colour at a resolution of better than 5 m (4.54m from a circular orbit of 400 km) for enhancing our knowledge of the surface of Mars [1].

CaSSIS is the only imager on-board and has been designed to both complement the other payload elements and to provide new observations of the surface of Mars. The core optical element of CaSSIS is the 135 mm (F/6.5) off-axis telescope designed, developed, assembled and tested by the former Opto-Electronics and Instrument division of RUAG Space Switzerland, now known as OEI Opto AG. Main technical challenges for the telescope were: i) mass optimization, with the CFRP structure significantly light-weighted; ii) power budget to regulate the temperature during both survival (7W) and operational phases (14.5W); iii) optical design constraints and the pre-compensation of the expected shrinkage of the CFRP structure caused by moisture release. But on top of the technical aspects, the very tight schedule provided the biggest challenge for the team.

The Phase C/D activities started in November 2013, manufacturing release review took place in March 2014 and finally the hardware was delivered to the University of Bern in July 2015. As the manufacturing time of the mirrors was longer than a year, it was clear from the beginning that a classical sequential approach was not feasible. Concurrent engineering was widely implemented in order to minimize the design cycle, which was the driver to start manufacturing of the optical elements.

The pragmatic approach taken for the CaSSIS telescope development, supported by the entire CaSSIS team at University of Bern and within ESA project, is presented in this paper together with a brief overview of the Instrument. The TGO spacecraft was launched successfully from Baikonur on 14 March 2016 at 09:31 UT, currently in the inter-planetary cruise and will encounter Mars on 19 October 2016. From the first in flight checks, the results are in good agreement with prediction [2-3].

II. OVERVIEW OF THE CASSIS TELESCOPE ASSEMBLY

The CaSSIS Telescope Assembly has been designed to support acquisition of both single images and stereo image pairs. The Telescope Assembly System comprises optical elements focusing the beam, mechanical mounts supporting the optical elements, the internal baffles, the field stop, and mounting structures for interfacing to the Rotation Drive and to the Focal Plane. A picture of the Flight Telescope is given in Fig. 1. The mass of the Telescope Assembly is 4626g. The assembly can be broken down as follows:

a) Optical Sub-System

b) Structural Sub-System

c) Thermal and Electrical Sub-system

A. Optical Sub-System

The optical system consists of a ø135 mm, f=880mm, F/6.5 off-axis 4× reflective telescope with a FoV of 0.878° in the plane of symmetry and 1.336° in the across-direction (Fig. 2.). The initial baseline considered a Three-Mirror-Anastigmat (TMA) with an intermediate image and an additional flat folding mirror. It turned out that such TMA would result with a Tertiary Mirror almost as big as the Primary Mirror and would never fit into the available volume. To find configurations with reduced element sizes, iterations were made of a system with 3 ideal lenses, keeping the Focal Length and overall length constrained and taking the element sizes as performance merits.

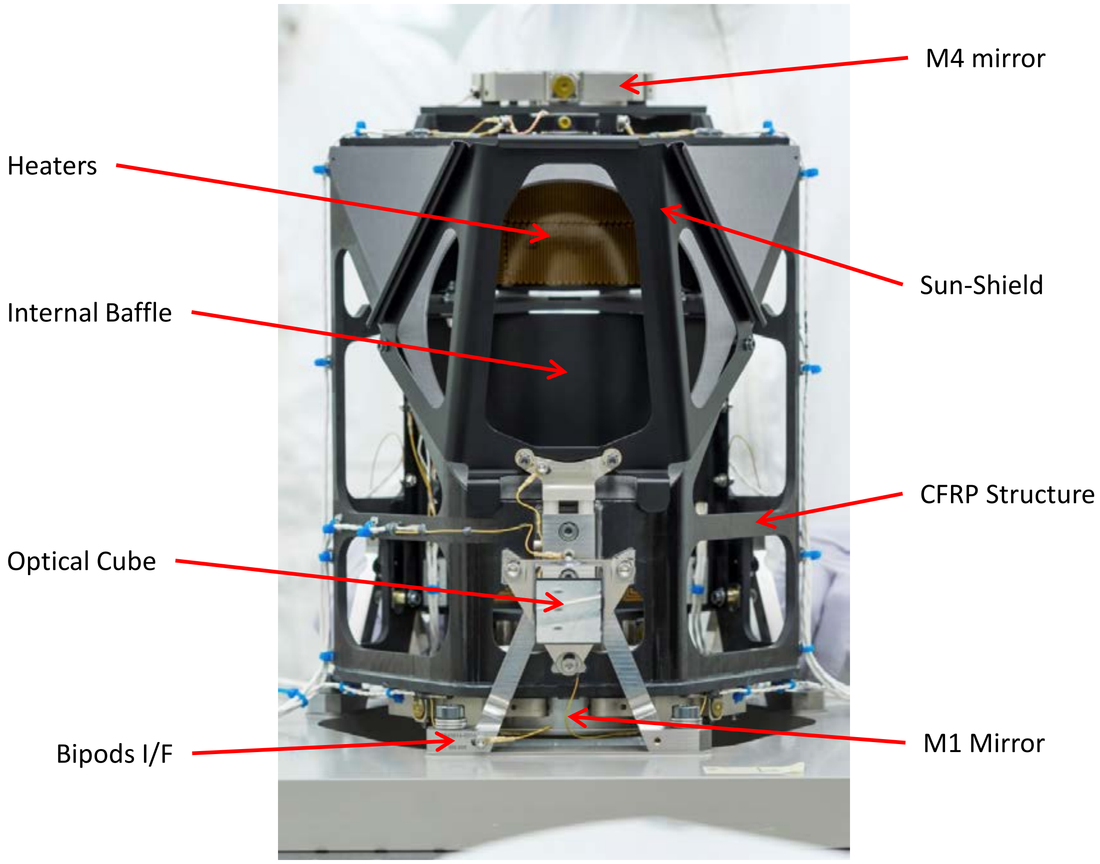

Fig. 1. CaSSIS Telescope Assembly

The only optical performance metric involved was the Petzval correction (the sum of the element powers to be zero). Two basic configurations emerged from this iteration:

i) one configuration with an intermediate afocal space and
ii) one configuration with a 1:1 imaging element.

The latter configuration would eventually result in a Korsch-like telescope with a minimum size Tertiary, yet the mirror would be too large.

Configuration i) was selected, which required 4 mirrors with optical power. In the transition from the ideal lenses to a design with real mirrors, the first element was substituted by a Cassegrain Telescope (M1, M2), yielding the intermediate image (a). The second element became the ocular mirror M3, yielding nearly collimated space (b). The third element became M4 and delivers the final image. Mirrors M3 and M4 are about the same size and have less than half the size compared to a single Tertiary Mirror of a TMA. This yields also a mass saving and likely also a cost saving. The increased DoF were further used to incorporate an existing Primary Mirror (from another telescope built in a small series at OEI Opto AG), thus eliminating the longest lead item. The severest drawback has been the loss of the flat folding mirror. The off-axis clearance had now to be achieved solely with tilts and decentres of the aspheric mirrors, which costs imaging performance. The most critical – and performance limiting – feature proved to be the clearance (c) between M3 and the beam underneath from M4 to the image.

The first order design had foreseen an accessible Exit Pupil for sake of Straylight suppression. This Pupil still exists (d), but there was no hope to achieve enough clearance. The remaining options for Straylight baffling were the placement of a Field Stop (e) at the intermediate image (a) and two intermediate walls (f), (g) which subdivide the telescope in an upper compartment with M1 and M2 and a lower compartment with M3 and M4. The optical design has further taken care to prevent direct sky view from the detector through the field stop into object space, line (h).

The overall imaging performance achieves an MTF of >0.3 at the detector Nyquist Frequency of 50 lines/mm (44 lines/mrad in object space) @λ=632nm over almost the whole Field of View, thus making optimal use of the detector (i.e. the MTF should also not be much more than 0.3 at the Nyquist Frequency to avoid aliasing effects [4])

The 4 aspheric mirrors are made of ZERODUR® Expansion Class 0. All four mirrors carry a protected Silver coating, by a process previously qualified by OEI Opto AG.

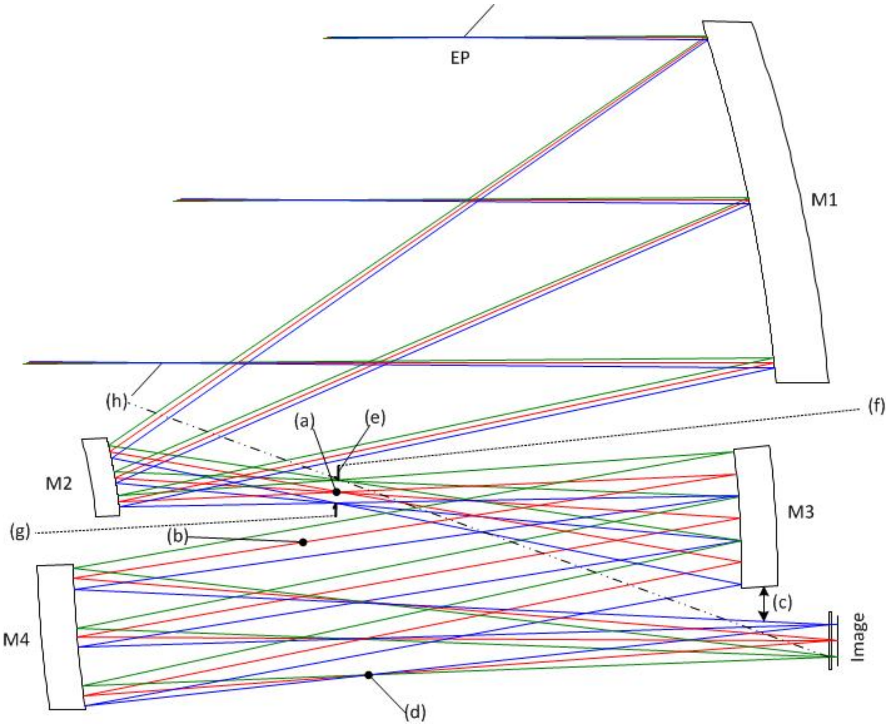

Fig. 2. CaSSIS optical design

B. Structural Sub-System

The key concept of the CaSSIS system is that it uses a rotation mechanism to produce the stereo pair [5]. The telescope in this case is not nadir-pointing but at an angle of 10° with respect to nadir. After acquisition of the first image, the telescope is rotated through 180° so that it points 10° stern.

A complexity introduced by the rotation is the need to ensure proper routing of the cables needed to drive the electronics. 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 interface between the Telescope Assembly and the Rotation Drive incorporates three Titanium bipods (Fig. 1.). The feet are then bolted to the Rotation Drive Mechanism with six Titanium M8 bolts. The bipods have been designed based on heritage to provide a highly stiff 3-points interface to the Telescope Assembly. They have been optimised several times during the development phase. VETRONITE® washers have been implemented at the Bipod interface to thermally isolate the Telescope Assembly from the Rotation Mechanism.

CFRP material has been used for the Telescope structure. The structure was reinforced throughout the development phase to increase its stiffness and its ability to withstand the random vibration loads.

The tube structure, which has a wall thickness of 4.8mm, was manufactured as one piece. Inserts were then added to the tube allowing it to be ready for receiving walls and other metallic structural components. The walls which are also 4.8mm thick are made in sheets from the same quasi-isotropic near zero CTE CFRP type, where they were then cut-out and machined to their required dimensions.

Optimising the mass of the Telescope Assembly has been a major effort throughout the development phase. One of the main reasons is that the strengthening of the structure following loads analysis has consumed a significant amount of the design contingency. The CFRP structure has been deeply light weighted, as can been seen in Fig. 3.

The structure has internal baffles. They are made of Aluminium and located adjacent to the Field Stop allowing them blocking unwanted optical paths from the entrance aperture to the FPA sensor, and radiatively and conductively transferring heat to the Telescope Assembly from a series of electrical heaters.

INVAR® mounts are attached to the CFRP tube, keeping the mirrors in place throughout the environmental changes and allowing testing in 1g gravity without significant degradation to the image.

Fig. 3. CaSSIS CRFP structure

C. Thermal and Electrical Sub-System

The Telescope Assembly thermal sub-system has to provide the ability to the Instrument to regulate the temperature of the Telescope Assembly during Survival and Operational phases. In addition it has also to provide the temperature of the Telescope Assembly to the S/C. For the survival phase 7W are needed by the Thermal sub-system. For the operational case 14.5W are needed to keep the Telescope Assembly at the operational temperature of 21±5°C. The thermal sub-system design is supported by the analysis (operational cold case in Fig. 4.), and has satisfied the above requirements by implementing heaters, thermostats and thermistors.

- 4 heaters are bonded to internal metallic baffles, 2 Nominal and 2 Redundant, each heater has a double circuit. The heaters are according ESA ESCC 4009-4009/002 and have unshielded wires according to ESCC 3901/020 04 AWG 24.
- The Telescope Assembly has 6 KLIXON® 3BT thermostats incorporated for regulating the heating power. Two are allocated for each heating zone (one nominal and one redundant). The cut-off temperatures of the thermostats is 60°. The harness shielded jacketed twisted pair according to ESCC 3901/012 54/0/9-9 AWG 24.
- 8 PT1000 temperature sensors are present, 6 for thermal control and 2 for providing read-out to the S/C. For the thermal control 3 are used during the Operational and 3 are used for the Survival Phase.

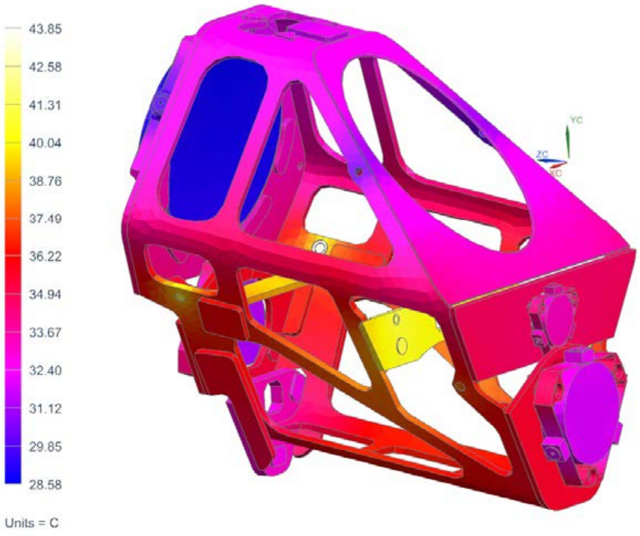

Fig. 4. CaSSIS Telescope operational Cold Case

III. DEVELOPMENT APPROACH

A. Schedule, phasing and risk mitigation activities

The scope of the project was to perform the full design, development, manufacturing, integration and testing of the Telescope Assembly, which consists of major sub-units at the technological edge. The project, which is currently in its operation phase E, was structured in sequential phases (B, C and D) with quality gates and major critical reviews in between.

The schedule control was the key driver from the very beginning, in order to comply with the overall schedule of the ExoMars launch. The launch was only possible in a limited time window (January-March 2016), due to the selected trajectory from Earth to Mars, with the next suitable window available only 2 years later.

Due to the very late final decision about the adoption of CaSSIS (Oct 2013), flying without this Instrument was an extreme but yet possible worst case considered by the ExoMars program. Therefore and in order to get as close as possible to the requested delivery time, a Proto-Flight model (PFM) development approach with specific risk mitigation activities has been agreed among the involved parties since the very beginning:

- 100% spare approach for the Mirrors and for the CFRP structure
- concurrent engineering for re-use in large extent of proprietary processes and materials already space-qualified for similar projects. The timeframe available didn't allow putting in place extensive space qualification programs;
- a simplified breadboard has been foreseen in parallel to the PFM to debug some of the manufacturing steps
- early and in time procurements for the schedule critical items, such as the Mirrors and the CRFP raw material;
- procurement of dedicated metrology equipment needed for the telescope integration and testing

The main objective of the phase B was the feasibility study for the design, assembly, integration and programmatic aspects. The phase B has been concluded with the Preliminary Design Review in November 2013. At the PDR the procurement of the Long Lead Items was kicked-off, together with the phase C. The phase C had the objective to consolidate the design, and it has been concluded with the Critical Design Review in March 2014. The implementation phase was split in two, with the phase D1 having the objective to perform the assembly and integration of the PFM, and the phase D2 with the objective to test and deliver the PFM. An overview of the major milestones and of the overall planning is schematically provided in the table Tab.1. below.

Tab. 1. CaSSIS Telescope phasing

Milestone	**End of**	**Start of**	**Date**	**Duration**
Preliminary Design Review	Phase B	Phase C	22.11.2013	-
Critical Design Review	Phase C	Phase D1	18.03.2014	4 months
Integration Readiness Review	-	-	23.10.2014	11 months
Test Readiness Review	Phase D1	Phase D2	26.05.2015	18 months
Test Review Board (delivery)	Phase D2	-	21.07.2015	20 months

B. Building-blocks and model philosophy

OEI Opto AG has extensive heritage in developing highly customized optical systems, with dedicated feasibility, development and design phases to finally deliver small series or even single units.

This was also the case of CaSSIS, with on top design freedom limitation dictated by the schedule impact. The scopes of the design were clear, and the objectives were inter-dependent (mass, power, volume, interface requirement and operational environmental conditions). In CaSSIS, a longer trade-off design iteration for a potentially improved design, could have meant missing the flight opportunity on board of ExoMars.

Having in mind the goal to comply with the challenging schedule, technological building blocks have been used as starting point. The technology philosophy of the CaSSIS Telescope Assembly has been to utilize as much as possible heritage from similar projects. This was realised through extensively re-use of technology used in other similar projects.

Without this solution the on-time manufacturing of CaSSIS couldn't be possible, from any other company worldwide (up to our knowledge) due to the lead time of the critical components. Here an example of the used building blocks:

- the optical design has been constrained to the use of an existing component (Primary Mirror), available as spare from another project
- the space qualified mirror mounting techniques available;
- the space qualified CFRP technology available;
- the available heritage from the telescope integration and metrology procedures;

Of course the environment for the ExoMars mission has different parameters compared to the other missions, resultingly there has been an effort from all the involved parties to minimise the impact of the environmental differences between the missions, by optimizing the Survival and Operating conditions to maintain the foreseen hardware within an already qualified environment. At the project start the Technology Readiness Level [6] of the overall system equipment was 5, as all of the technologies and processes were qualified at component level for the Environmental conditions. Due to the high specificity of the application and the singularity of the requirements, fine tuning, delta-qualifications and technological innovations was also necessary. Examples are the combination of thermal control with low thermal conductive materials, and the qualification against the aero-breaking requirement.

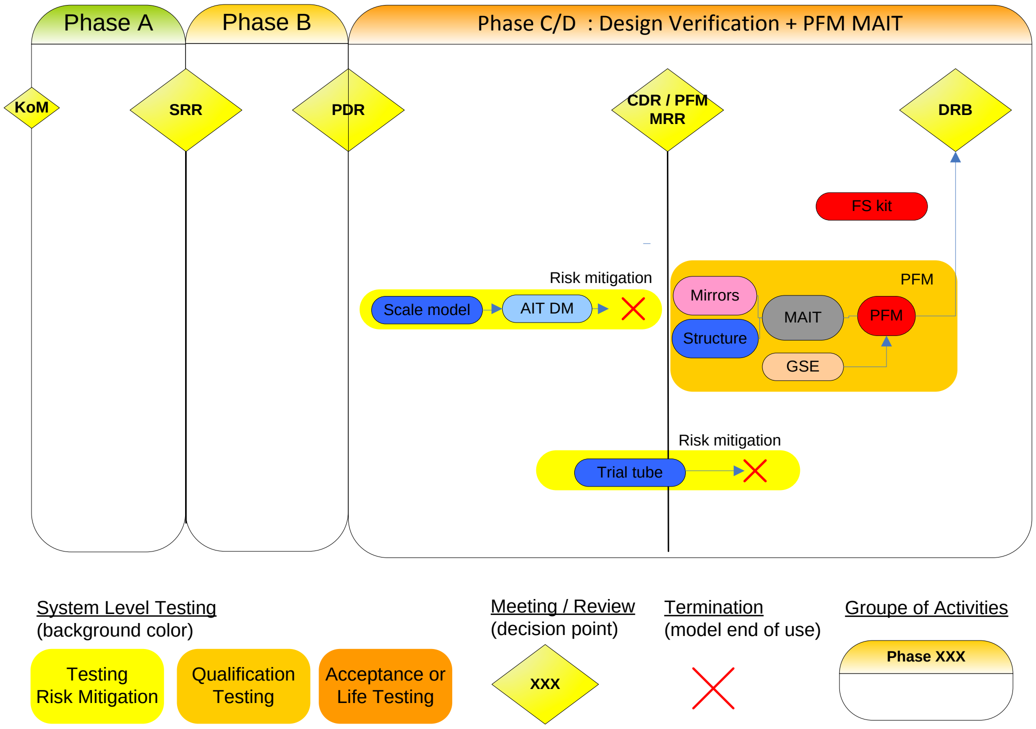

Fig. 5. CaSSIS Telescope Assembly Models Flow

C. *Synergy of testing campaign*

Due to the time scales imposed on the project, critical bread-boarding in parallel with a basic Development Model followed by a PFM approach was the only viable model philosophy to be taken forwards. The components for a Flight Spare have been as well procured which could be assembled, integrated and tested in the event of a major issue occurring.

Based on the above presented considerations, the development and verification approach included a combination of acceptance at component/sample level (e.g. mirrors, EEE, CFRP material, etc.) and at assembly level. The adopted Acceptance Test Flow is showed in Fig. 6.

A pragmatic decision was taken, about deviating from the requirement to Shock test the PFM unit. It has been possible to prove that the CaSSIS shock level was covered by similarity, from previous qualification programs for the more critical component (Primary Mirror). This is another good example of how CaSSIS benefited from the use of building blocks.

The CaSSIS Telescope was delivered to the University of Bern for completing the acceptance. The University of Bern was indeed responsible for the mounting of the detector to the telescope, and hence the Thermal Vacuum test has been performed in synergy with the complete CaSSIS Instrument. 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 shrinkage of the CFRP structure by moisture release [2]. This has been based on the prediction from the well mastered CFRP modelling at OEI Opto AG, and this turned out to be the optimum testing sequence.

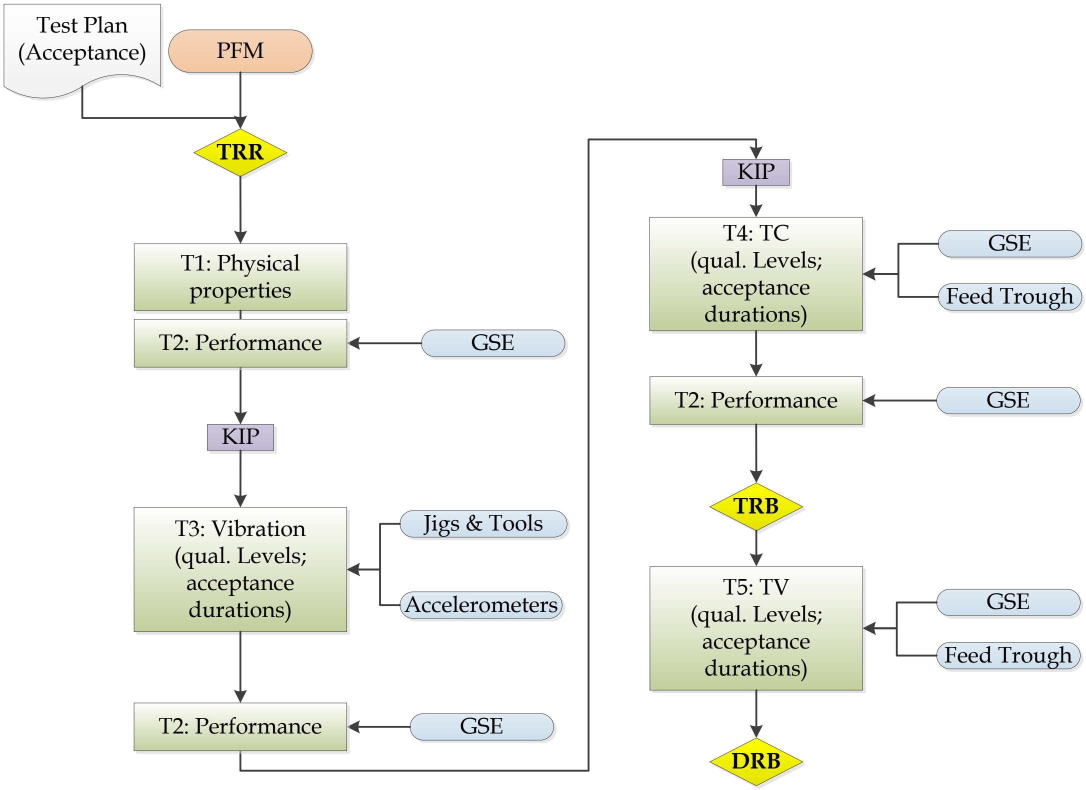

Fig. 6. CaSSIS Telescope Assembly Test Flow

IV. CONCLUSION

The telescope of the Camera CaSSIS (Colour and Stereo Surface Imaging System) has been presented. It achieves a ground resolution of 4.6 meter/pixel from an altitude of 400 km. It is a Ø135 mm f=880mm F/6.5 with a rectangular Field of View of 0.878° in the plane of symmetry (along track) and 1.336° across it. The opto-mechanical configuration follows a zero-expansion approach with mirrors of Zerodur, Invar mounts and a CFRP open-tube structure. The active thermal system stabilizes the telescope to a range of 21±5°.

The activities started in November 2013, manufacturing release review took place in March 2014 and finally the hardware was delivered to University of Bern in July 2015. The portfolio of “building blocks”, in terms of processes, design solutions, supplier basis, integration procedures and equipment available in OEI Opto AG, was the key ingredient to “make it happen” in the given timeframe. The pragmatic approach taken for the CaSSIS telescope development, supported by the entire CaSSIS team at University of Bern and within ESA project, should be an example worth to be repeated. CaSSIS achieved First Light in space on 7. April 2016 with a starry view to the southern celestial pole, and the results are in good agreement with prediction.

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REFERENCES

[1] N. Thomas et al., "The Colour and Stereo Surface Imaging System for ESA's Trace Gas Orbiter," *Planetary and Space Science*, in press

[2] L. Gambicorti et al., "First light of CaSSIS - the stereo surface imaging system onboard the ExoMars TGO," ICSO 2016, this conference

[3] L. Gambicorti et al., "The CaSSIS imaging system: optical performance overview," SPIE Vol. 9904, 99041E (2016), [4] R. D. Fiete and B. D. Paul, " Modeling the optical transfer function in the imaging chain," *Optical Engineering,* vol. 53 (8), August 2014.

[5] A.S. McEwen et al., "Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE)," *Journal of Geophysical Research (Planets)*, 112, E05S02.

[6] ISO 16290:2013, "*Space systems -- Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment."*