

CO2M EARTH OBSERVATION TELESCOPE DEVELOPMENT AND TESTING

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ABSTRACT

The Copernicus CO₂ Monitoring (CO₂M) satellite is a key component of the European initiative for CO₂ Monitoring and Verification Support (CO₂MVS), designed to monitor global anthropogenic CO₂ and CH₄ emissions. Thales Alenia Space in Switzerland (TAS-CH) developed the telescope for the CO₂ Imaging Spectrometer (CO₂I), one of the three primary instruments on-board CO₂M.

The telescope serves to depolarize light reflected from the Earth's atmosphere and guide it into the near-infrared and shortwave-infrared spectrometer.

The CO₂M telescope features an off-axis Three Mirror Anastigmat (TMA) optical design, supplemented by two folding mirrors at both the entrance and exit to meet interface requirements.

A polarization scrambler, based on the Babinet principle and utilizing pairs of wedged birefringent prisms made of crystal quartz, is located at the Telescope entrance. A custom optical coating for the scrambler was developed and qualified to ensure optimal performance.

The main technical challenges in the Telescope's development included:

- integrating the complex optical system within a robust and thermally stable opto-mechanical structure;
- achieving mass optimization, necessitating significant light-weighting of the larger glass mirrors;
- designing and implementing the polarization scrambler;
- developing strategies for optical alignment, assembly, integration, and testing (AIT), along with the associated ground support equipment.

This paper presents the implemented optical and thermo-mechanical design solution for the CO₂M Telescope and provides an overview of the manufacturing process, as well as the assembly, integration, and testing (AIT) activities of the Proto-Flight Model (PFM).

Keywords: Space, Telescope, CO₂M, WFE, CFRP, Mirrors, Zerodur®

INTRODUCTION

The Copernicus CO₂ Monitoring (CO₂M) satellite is a cornerstone of the European CO₂ Monitoring and Verification Support initiative, aimed at tracking global anthropogenic CO₂ and CH₄ emissions. Thales Alenia Space Switzerland (TAS-CH) developed the Telescope for the CO₂ Imaging Spectrometer (CO₂I), one of the satellite's three primary instruments.

The CO₂M Telescope employs an off-axis Three Mirror Anastigmat (TMA) optical design, complemented by folding mirrors to comply with interface constraints. A polarization scrambler, based on the Babinet principle with wedged birefringent crystal quartz prisms and custom coatings, is integrated at the Telescope entrance to depolarize incoming light and optimize spectrometer performance.

This paper describes the work done by Thales Alenia Space on the CO₂M Telescope, addressing key development challenges such as integrating a complex optical system into a robust, thermally stable structure; optimizing mass through mirror light-weighting; designing the polarization scrambler; and conducting manufacturing, assembly, integration, and testing (AIT) activities of the Proto-Flight Model (PFM).

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1. MAIN DESIGN DRIVERS

This section details the primary technical drivers for the CO2M Telescope design, encompassing both optical and thermo-mechanical requirements.

1.1 Optical Requirements

As with all telescopes, optical quality is the foremost requirement. For the CO2M telescope, this is specified in terms of Wavefront Error (WFE), which is relatively straightforward to measure. An additional advantage of this measurement is that it can be used during integration to optimize mirror positioning, even once all mirrors are in place. Although the WFE requirements for this telescope are not extremely stringent, the large field of view complicates mirror alignment and characterization.

The CO2M telescope has a unique feature: the scrambler. The presence of the scrambler complicates WFE measurement because each beam is split into eight sub-beams. Consequently, the requirements are divided into two parts: WFE for the scrambler and WFE for the telescope itself. The challenges associated with measuring the scrambler's WFE are discussed in detail in the following chapter.

In addition to WFE, polarization and transmission are critical requirements and must be addressed through appropriate scrambler design and coating selection.

Another key requirement is the stability of the Line of Sight (LoS). To ensure accurate co-registration between instruments, LoS stability is essential. This consideration was a primary driver in the telescope's structural design. Thermal stability and moisture release effects were carefully accounted for in both material selection and mechanical design to maintain symmetry, even with the three-dimensional folding of the optical layout.

1.2 Thermo-Mechanical Requirements

The CO2M Telescope Unit is designed to be mounted on the Ultra Stable Interface Bench (USIB), which serves as the common mechanical interface for the optical instrument (cf. Figure 1-1). Although housed within the satellite and thus protected from external thermal and radiative effects of space, the thermo-mechanical design of the Telescope faced significant challenges. These arose from the need to achieve stringent optical stability performance while contending with the satellite's non-uniform thermal environment.

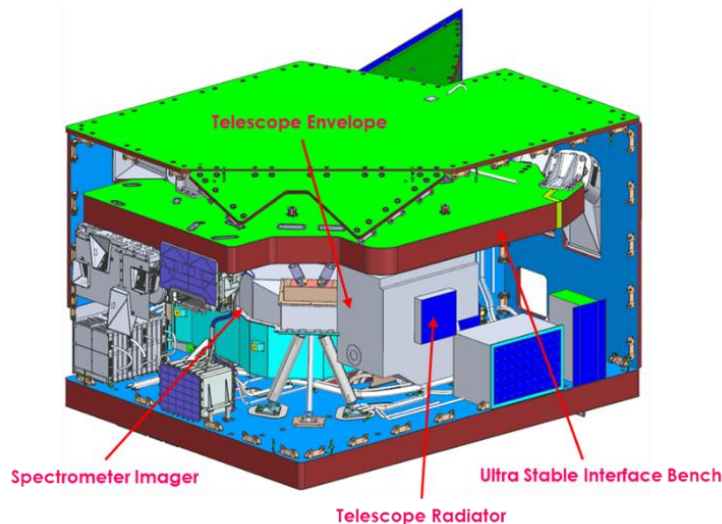


Figure 1-1: Section of the CO2M instrument with Telescope envelope and its thermo-mechanical interfaces against the USIB

As mentioned above, the non-uniform thermal environment during operational conditions was a key driver in the design of the Telescope. Although the satellite internal cavity mitigates the constraints associated with the non-operative temperature range (-15°C to 25°C), the Telescope must effectively manage both conductive and radiative thermal interfaces with its surrounding environment and supporting structure. The conductive interface is established through the mechanical connection with the USIB, while the radiative interface occurs between the Telescope and the internal

environment of the spacecraft, which includes a stable radiative cold sink provided by the radiator facing the Telescope. A simplified overview is illustrated in Figure 1-2.

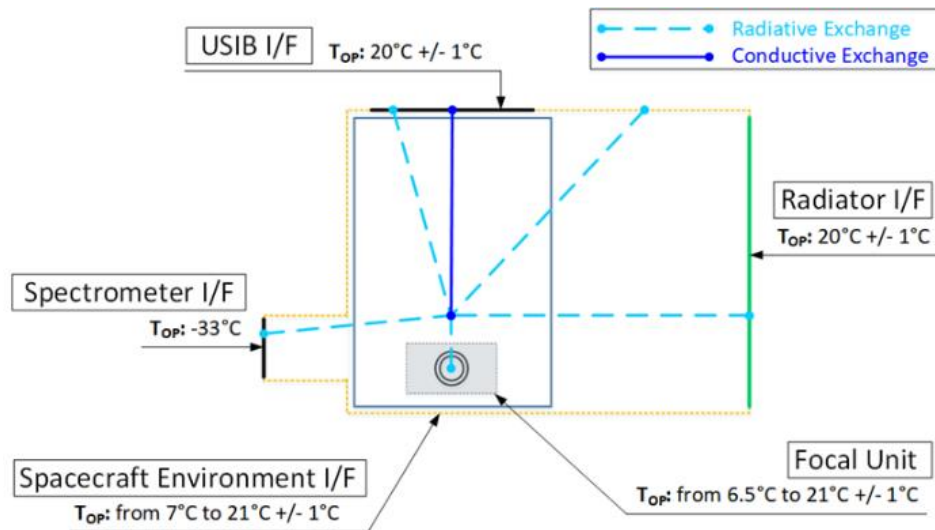


Figure 1-2 Schematic of the thermal environment of the CO2M Tel.

Despite the stable conductive and radiative links ensured by the USIB and the radiator, both maintained at 20°C, the Telescope's thermal boundary conditions exhibited the following characteristics:

- Spectrometer aperture, telescope output side, maintained at 33°C
- The Focal Unit, telescope input side, whose operating temperature varying between 6°C and 25°C
- The Spacecraft operating environment temperature ranging from 7°C to 21°C

These boundary conditions posed a risk of creating thermal gradients across the Telescope structure, which could adversely affect its optical stability performances. Such effects needed to be mitigated through careful design and the selection of appropriate materials.

Specific STOP (Structural, Thermal, and Optical Performance) analyses and design trade-offs were conducted during the development phase with the goal of minimizing the detrimental effects of thermal gradients under in-orbit conditions.

The mechanical design of the CO2M Telescope is complex due to the need to satisfy multiple critical, and sometimes conflicting, requirements:

- Volume, Mass, and Stiffness:
 - o The Telescope must fit within a tight volume to keep the overall CO2M instrument compact.
 - o Maximizing the stiffness-to-mass ratio is a key requirement for spacecraft equipment to ensure mechanical efficiency and performance.
- Optical Layout:
 - o The structure must accommodate the beam path with sufficient margins, defining a stay-out zone throughout the Telescope.
 - o Robust structural support for all optical elements is essential
- Mechanical Support:
 - o The Telescope mechanical support is located at a distance from the optical elements
- Strength and Stability:
 - o The Telescope structure must withstand the demanding launch environment and must cope with Space vacuum.
 - o It must also maintain structural stability during operation in space to ensure the required optical performance.
- Manufacturing, Assembly, Integration, and Testing (MAIT):
 - o Components shall be manufacturable and the structural design must facilitate all necessary assembly, integration, testing, and characterization steps.
- Surface Finish:

- The structure must be cleanable and offer appropriate thermo-optical surface properties (optimize radiative heat transfer and minimize stray-light effects).

Given the CO2M instrument layout, the optical elements of the CO2M Telescope are positioned at a considerable distance from its structural support at the USIB (optical layout barycenter approximately 150 mm away from USIB).

This configuration creates two key needs:

- 1) A dedicated component is needed to bridge the gap between the USIB and the optical assembly. This component must be robust enough to support the optics throughout all operational and non-operational phases.
- 2) Strict optimization of mass and stiffness is essential for both the optics assembly and the bridging structure. This is necessary to comply with the overall CO2M Telescope mass limit of 10 kg and to minimize any vibration amplification caused by dynamic environmental loads across the Telescope.

2. TELESCOPE DESIGN SOLUTION BY TAS-CH

2.1 Optical Design Solution

The proposed solution for the CO2M Telescope must address several key requirements, with the primary optical performance considerations including:

- High optical quality across a large field of view
- Accommodation of beam folding within a three-dimensional optical path
- Implementation of a field stop
- Effective polarization scrambling

Although the aperture is relatively small - 30 mm in diameter compared to other instrument telescopes - the CO2M telescope itself is physically large due to the extensive field of view to be covered. For instance, while the entrance pupil measures 30 mm in diameter, the beam footprint on the primary mirror (M1) spans approximately 133 mm by 31 mm. The largest mirror, M3, receives a beam footprint measuring about 128 mm by 112 mm.

Optical Design. The CO2M Telescope design is based on a standard Three-Mirror Anastigmat (TMA) configuration. Two folding mirrors, positioned at the telescope's entrance and exit, are incorporated to route the beam and appropriately position the interface. This double folding approach did not significantly complicate the optical design but did have an impact on the Integration, Verification, and Validation (IVV) activities. The corresponding telescope layout, in which all mirrors lie within a single plane except for the secondary folding mirror (FM2), is presented in Figure 2-1 and Figure 2-2.

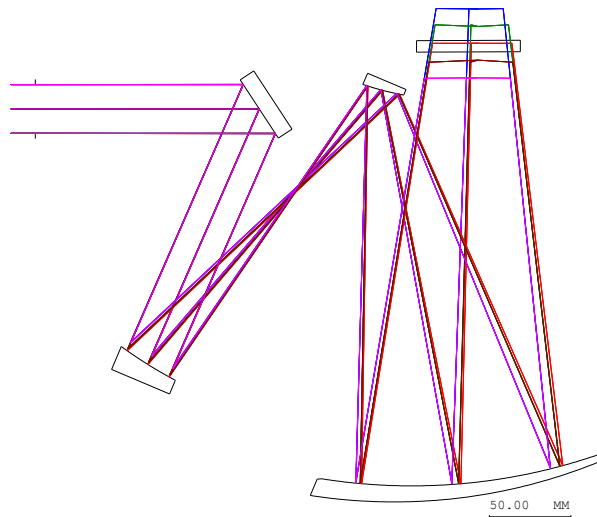


Figure 2-1 2D representation of TMA optical layout

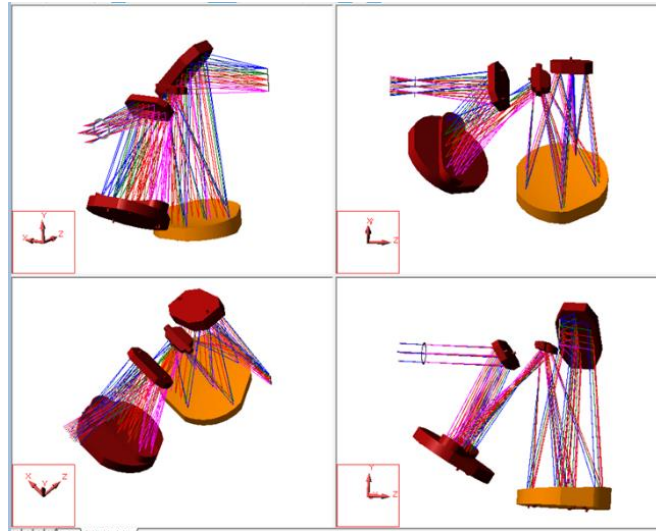


Figure 2-2 3D visualization of TMA optical layout. Each color corresponds to an (angular) field

Aspherical Mirrors. Given the numerous optical performance requirements and overall constraints on the system, and considering the TMA architecture, the use of simple spherical or conical surfaces is not feasible. Conversely, there is no inherent justification for employing freeform optics, which would introduce several drawbacks, including increased cost, complex metrology, and prolonged alignment times. Therefore, an intermediate approach was adopted by utilizing aspheric surfaces. The optical design incorporates aspherics up to the fourth order.

Field Stop. To minimize stray light within the CO2M telescope and instrument, a compartmentalized design approach has been adopted. The telescope is divided into two compartments: the first contains the Folding Mirror 1 (FM1) and Mirror 1 (M1), while the second houses the remaining mirrors. This configuration prevents stray light generated in the first compartment from propagating to the second compartment and subsequently reaching the focal plane. To further enhance stray light suppression, a field stop has been introduced to isolate the two compartments as effectively as possible. Due to stringent tolerance requirements, the field stop had to be integrated downstream of the mirrors, and its position was adjusted to match the as-built optical path.

Scrambler. A Polarization Scrambling Device is required at the telescope's entrance pupil to ensure that the signal measured by the spectrometer is insensitive to the polarization state of the incoming light. Since fully depolarizing a polarized beam without degrading wavefront quality is not feasible, the practical approach is to produce a spatially varying polarization state across the pupil for a given point source, effectively creating a pseudo-random polarization distribution.

This spatial variation can be achieved by locally modulating the optical path difference between the s- and p-polarization components of the incoming beam. Such varying retardance is typically implemented using one or more Babinet compensators, which have been successfully deployed in orbit on scientific observation instruments.

The scrambler design employed here is based on the Babinet compensator concept. Each Babinet component consists of a pair of wedged birefringent quartz prisms bonded together (cf. Figure 2-3). The prisms are identical in material and wedge angle but are oriented symmetrically with crossed crystal axes rotated by 90° relative to one another.

To achieve the required scrambling performance, the device incorporates three Babinet compensators in series. The main technical advantages of this approach include effective polarization scrambling, low internal flux loss, and a compact form factor. However, a key drawback is that the output beam is angularly split into multiple directions—specifically 2^n beams for n Babinet components—resulting in a ground-point spread function (PSF) composed of up to eight discrete spots for the triple-Babinet configuration.

A dedicated qualified adhesive was selected due to its heritage at TAS-CH, optical clarity across all relevant wavelengths, and suitability for space applications.

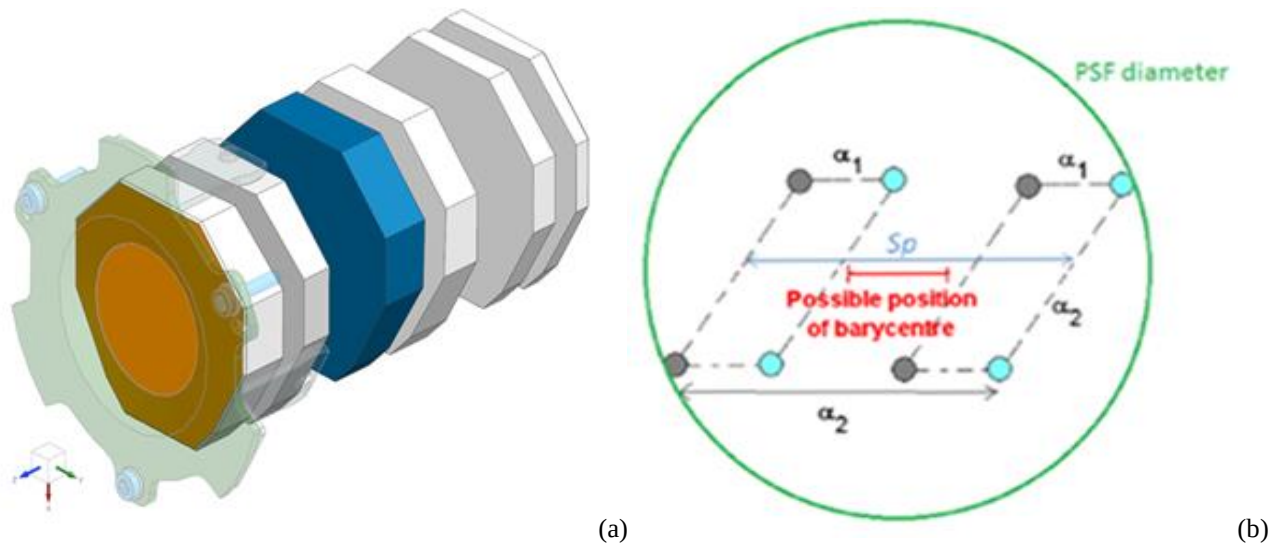


Figure 2-3: Isometric view of Scrambler Assembly (a); Disposition of beams after Scrambler Assembly (b)

2.2 Thermo-Mechanical Design Solution

The design of the CO2M Telescope unit has been developed to meet the various constraints and requirements outlined in section II.B. Figure 2-4 presents an overview of the chosen design, highlighting the main sub-assemblies: the Telescope assembly itself and the supporting bridging structure. For clarity, the Multi-Layer Insulation (MLI) surrounding the Telescope has been omitted in Figure 2-4.

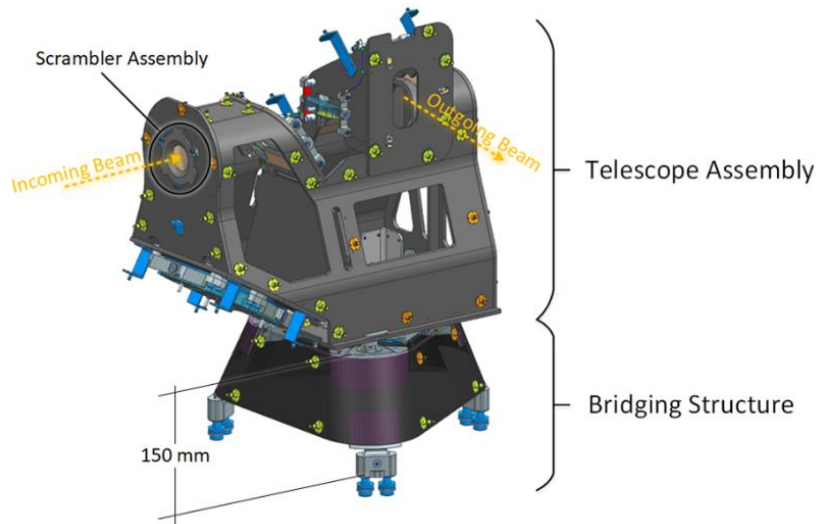


Figure 2-4: Overview of CO2M Telescope unit design solution

The CO2M Telescope Assembly provides the primary optical functions. It houses the three main Telescope mirrors and the two folding mirrors, which together compose the optical layout described in section A. Additionally, the Scrambler Assembly, whose purpose is to depolarize the incoming light, is also part of the Telescope Assembly. At the core of the Scrambler Assembly are six quartz wedges, bonded together to form the scrambler itself, whose geometry has been developed to meet the depolarization requirements outlined in section II.A. Similar to the other optical components, the Scrambler holder has been engineered to reduce stress on the glass components, while ensuring the thermal stability of the assembly during operational phases. Fig. 7 presents a picture of the assembled Scrambler hardware.

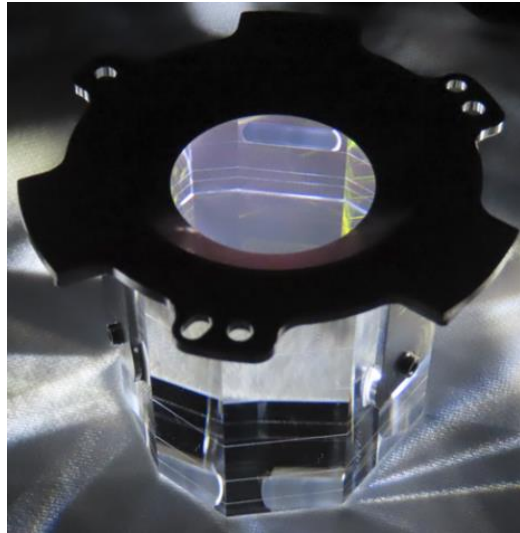


Figure 2-5: Picture of the machined and assembled Scrambler

In addition to its structural function, the Scrambler holder has been engineered to fulfil two additional functions:

- Optical function: establishing the entrance pupil reference for the Telescope Assembly
- Integration function: enabling repeated dismounting and remounting of the Scrambler during the assembly, integration, and testing phases without compromising its alignment with respect to the Telescope Assembly

The Bridging Structure serves a purely structural role, spanning the distance between the USIB and the Telescope Assembly to ensure stable support for the Telescope's optical components under all environmental loads. Its current triangular design has been optimized to minimize any impact on the Telescope's optical stability during operational thermal conditions. The CO2M Telescope unit is mounted to the USIB using three pairs of MJ10 titanium bolts.

All materials used in the Telescope have been carefully selected to meet both, the stringent optical stability requirements and to minimize the total mass of the optical unit, while ensuring the overall robustness of the structure:

- Carbon fiber laminate and Invar with NiP blank coating inserts for both Telescope and Bridging structures
- Invar with NiP blank coating for optics holders
- Zerodur® for all the mirrors

In particular, the choice of carbon fiber laminate for the entire Telescope Unit structure was motivated by TAS-CH's heritage with this material and relative manufacturing processes. It combines a very low in-plane coefficient of thermal expansion (CTE) with a very low coefficient of moisture expansion (CME), which was specifically characterized in the frame of CO2M Telescope project. The result is a structural design, which minimize the optical distortions under operative thermal and vacuum conditions in-orbit.

To further reduce mass and consequently decrease localized stress on the optics holders under dynamic loads, a light-weight design has been implemented for the larger mirrors (M1, M3, and FM2), achieving up to a 60% reduction in mass compared to the original solid volume. Figure 2-6 illustrates this approach for mirror M1, which has been light-weighted by back-pocketing.

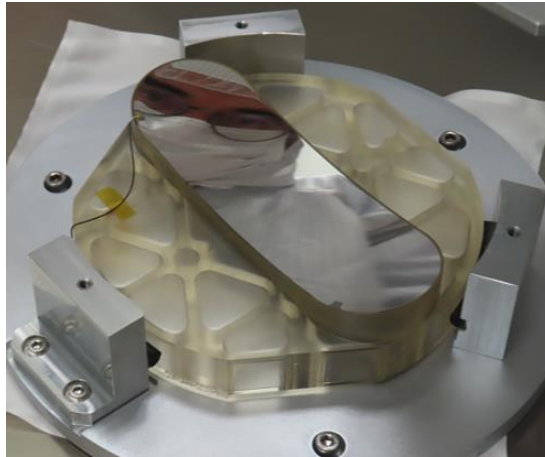


Figure 2-6: Picture of light-weighted mirror M1 from Zerodur® with silver coating

3. TELESCOPE UNIT INTEGRATION AND TESTING

Another significant challenge of the CO2M Telescope project was developing a robust and efficient strategy for:

- the assembly and integration of all optical components within the structure
- optical alignment procedures that ensure the required performance levels
- testing methods to qualify the design under non-operational loads and verify performance stability during operational conditions

With the completion of the Proto-Flight Model (PFM) test campaign, it is now possible to summarize the challenges encountered during the qualification phase, as well as the performance results of the actual hardware.

3.1 Telescope Unit Assembling and Integration

Fig 9 presents a flow diagram summarizing the assembly and integration process of the CO2M Telescope Unit Proto-Flight Model.

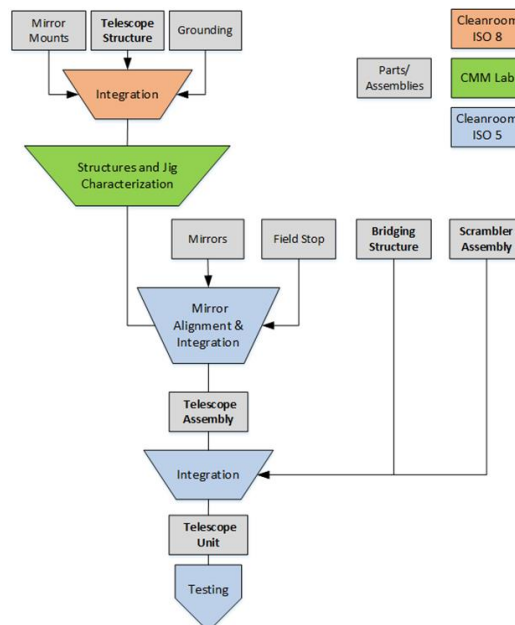


Figure 3-1 Telescope Assembly and Integration Flow

Following the assembly of the Telescope Structure and Bridging Structure, an extensive mechanical characterization of these components, as well as the entire alignment jig, was conducted. This step is critical because the Telescope Assembly can only be integrated onto the Bridging Structure after the mirrors have been precisely aligned. This integration constraint is driven by the complexity of the optical layout - particularly the relative positioning of the mirrors and the double-folding beam architecture described in section III.A, which significantly restricts access to and manipulation of the optics during alignment.

Once the Telescope Assembly and Bridging Structure are integrated, a comprehensive set of optical measurements is performed to verify compliance with the required performance specifications. This integrated configuration defines the flight configuration and serves as the baseline for subsequent optical stability assessments during the qualification test campaign.

The wavefront error (WFE) results obtained at the conclusion of the integration phase are summarized in Table 3-1. These WFE are well within the required error of 300 nm RMS defined in the Customer specification.

Table 3-1 WFE results obtained at the end of the integration phase for different FoV

FoV [°]	WFE RMS [nm]
10	163
4	87
0	103
-4	84
-10	114

The results presented in Table 3-1 served as a reference for direct comparison with measurements obtained at each stage of the test campaign.

Due to its unique scrambling behavior, as described in section III.A, the Scrambler Assembly is excluded from the wavefront error (WFE) measurements of the integrated telescope. Specifically, the presence of the scrambler prevents accurate WFE assessment within the interferometer, as the returning beam is composed of eight distinct wavefronts. Consequently, the Scrambler Assembly's WFE performance has been evaluated independently using a dedicated test setup, illustrated in Fig 10.

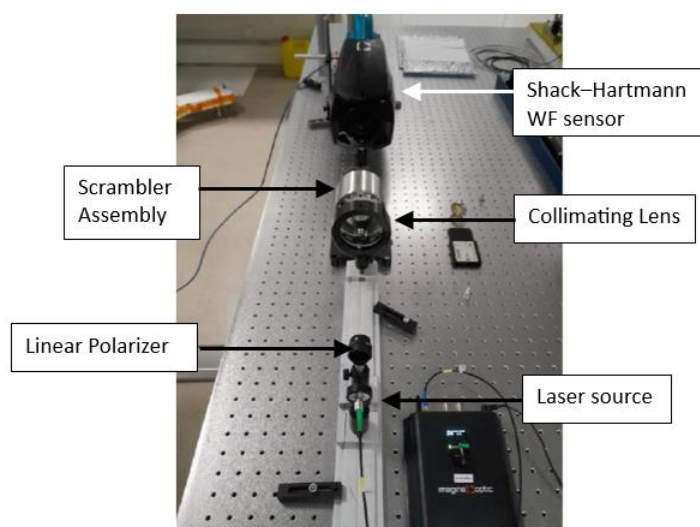


Figure 3-2 Scrambler Assembly WFE measurement setup.

The primary objective of this measurement setup is to isolate a single one of the eight output spots produced by the Scrambler using spatial filtering, and subsequently measure its wavefront error (WFE) with a Shack–Hartmann sensor. The WFE results obtained for the Proto-Flight Model (PFM) Scrambler Assembly are summarized in Table 3-2. These WFE are well within the required error of 150 nm RMS derived from the Customer specification.

Table 3-2 WFE results for the PFM Scrambler Assembly

FoV [°]	WFE RMS [nm]
10	69
4	68
0	69
-4	70
-10	71

The need to perform separate wavefront error (WFE) measurements for both the Telescope Unit and the Scrambler Assembly is the primary reason for multiple removals of the Scrambler Assembly from the telescope during the test campaign. Accordingly, the test sequence was optimized to:

- Include the Scrambler Assembly during the qualification of the complete flight configuration
- Minimize the number of Scrambler Assembly removals required to optically verify the Telescope Unit's integrity following exposure to environmental loads.

3.2 Telescope Unit Testing

Following the integration and alignment of the CO2M Telescope Unit, the test phase is initiated. The flow diagram in Fig. 11 provides an overview of the qualification test campaign for the Proto-Flight Model.

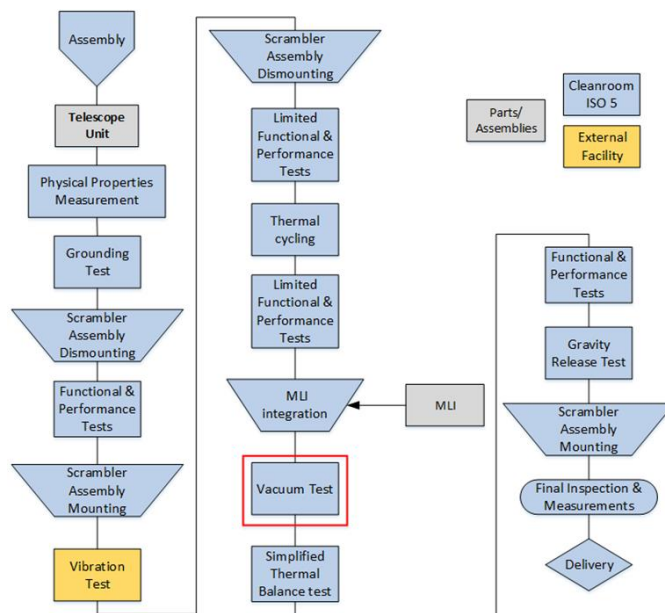


Figure 3-3 CO2M Telescope unit test flow (Current step: Vacuum Test).

To provide a comprehensive overview of the CO2M Telescope Unit test campaign, the following key points should be noted:

- Due to its complex geometry and numerous interface points with the Telescope Unit structure, the Multi-Layer Insulation (MLI) is installed only after completion of environmental tests (i.e., vibration and thermal cycling). This approach simplifies the installation and removal of test instrumentation during the Proto-Flight Model (PFM) qualification.
- The Scrambler Assembly underwent a separate thermal cycling test, aiming to significantly reduce the number of disassembly and reassembly operations throughout the test campaign.
- During vibration testing conducted at an external facility, the Telescope Unit was enclosed in a bag with continuous nitrogen purging to maintain the required cleanliness standards.

At the time of writing, the PFM Telescope Unit has successfully completed the qualification campaigns for vibration and thermal cycling under non-operational conditions and is preparing to commence the vacuum test.

All tests conducted to date have been passed successfully, demonstrating that the Telescope Unit design:

- Can withstand the severe launch loads and in-orbit non-operational conditions.
- Maintains stability without degradation of the required optical performance, thereby confirming the structure's excellent thermo-mechanical stability.

4. CONCLUSIONS AND NEXT STEPS

The CO2M Telescope Unit development has successfully addressed the complex thermo-mechanical, optical, and integration challenges outlined in the project requirements. The telescope's design, leveraging advanced materials such as carbon fiber laminates, Invar with NiP coatings, and Zerodur® mirrors, has demonstrated excellent thermo-mechanical stability and robustness against expected environmental loads.

The light-weighting of primary mirrors and the structural optimization of the telescope and bridging structures effectively minimize mass while maintaining stringent optical stability. The inclusion of the Scrambler Assembly, designed to depolarize incoming light without compromising alignment, adds significant value to the unit's optical performance.

Throughout the assembly and integration phase, mechanical and optical alignment procedures ensured that the complex optical layout, especially with double-folding mirrors and scrambler components, met the wavefront error (WFE) requirements. The separate evaluation of the Scrambler Assembly's WFE further ensured individual component performance without interference from the unique scrambling effect.

The Proto-Flight Model has undergone a thorough qualification campaign including vibration, thermal cycling, and preparation for vacuum testing. All tests performed thus far have been successfully passed, confirming the CO2M Telescope Unit's capability to withstand launch and in-orbit non-operational environments while maintaining the required optical performance.

Next Steps:

- Completion of the vacuum testing phase to validate telescope performance under operational space environment conditions.
- Final verification and validation of the integrated unit with the spacecraft bus to ensure system-level compatibility.
- Preparation and execution of flight model production leveraging lessons learned from the Proto-Flight Model.
- Continued refinement of assembly, integration, and testing procedures to optimize build time and alignment reproducibility for the next models.
- This systematic approach confirms the CO2M Telescope Unit's readiness for spaceflight and provides a solid foundation for the mission's success in delivering high-precision observations.

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