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DESIGN AND PERFORMANCE OF THE TANGO INSTRUMENTS FOR GREENHOUSE GAS DETECTION

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ABSTRACT

The Twin ANthropogenic Greenhouse Gas Observers (TANGO) mission will measure CO_2, CH_4 and NO_2 emissions at the level of individual facilities. A consortium consisting of ISISPACE (mission and satellite prime), SRON and KNMI (atmospheric science) and TNO (instruments prime) has been selected for the implementation of the TANGO mission which belongs to the ESA Scout framework, with a schedule of three years from implementation kick-off until launch.

The TANGO space segment consists of two agile 16U CubeSat satellites flying within one minute of each other, each equipped with an imaging spectrometer. TANGO Carbon measures the emission of CH_4 and CO_2 in the SWIR1 spectral band, while TANGO Nitro measures the emission of NO_2 in the visible spectral range. Both instruments are reflective push-broom spectrometers, made almost entirely from aluminium, and will cover a 30-km swath from a 500-km altitude, with a spatial resolution <300 m in both across- and along-track. The instruments share a similar architecture, using freeform mirrors to achieve a high optical performance in a compact 8U envelope.

In this paper, we share the current design status of both instruments, where a key engineering challenge is to fit each one in an 8U volume while achieving the desired spatial resolution and SNR. In addition, we present the TANGO Carbon instrument Structural Thermal Model (STM) that was realized and tested.

Keywords: Earth observation, CO2, CH4, NO2, Atmospheric Science, Imaging spectrometer, TANGO, Scout

1. INTRODUCTION

Global warming and its major consequence climate change is one of the most urgent problems that humanity faces today. Climate change affects everything from environment to health, from geopolitics to economics with an increasing risk on life on Earth. According to the recent report of the Intergovernmental Panel on Climate Change [1], Earth's surface temperature has risen by 1.1°C above 1850-1900 during the last decade. Human activities, mainly through greenhouse gas emissions is the main cause of observed global warming. IPCC has indicated that crossing 1.5°C threshold level in global warming would bring more severe climate change impacts that cannot be reversed.

In 2015, the Paris Agreement [2] was signed by 195 parties at the 2015 United Nations Climate Change Conference (UNCCC) near Paris, France, as a legally binding international treaty on climate change. The goal of this agreement is to keep the rise of global temperature to well below 2°C compared to pre-industrial levels. To achieve this temperature goal, the level of greenhouse gas emissions should be managed well and reduced as much as possible which requires continuous measurements of these gases in order to take correct mitigation actions.

The Twin ANthropogenic Greenhouse Gas Observers (TANGO) mission has been developed to measure the two most important greenhouse gases CO2 and CH4 together with NO2 to support combatting climate change. TANGO will measure these trace gases at the level of individual facilities such as power plants, industrial plants, and oil and gas production facilities all over the world. The consortium of ISISPACE (Innovative Solutions in Space, mission and platform prime), TNO (Netherlands Organisation for Applied Scientific Research, instruments prime), SRON (Netherlands Institute for Space Research, atmospheric science (CO2 and CH4)) and KNMI (Royal Netherlands Meteorological Institute, atmospheric science (NO2)) has been developing the TANGO mission since 2019 in the scope of European Space Agency SCOUT framework, as a low-cost and fast-track development CubeSat mission.

This paper will present the TANGO mission in brief and introduce the two TANGO instruments; TANGO Carbon to measure CO2 and CH4, and TANGO Nitro to measure NO2.

2. THE TANGO MISSION ARCHITECTURE

In order to achieve the mission objectives the TANGO architecture consists of the following elements (Figure **2-1**):

- Launch Segment that consist of the launcher itself and the ISISPACE standard deployer system.
- Space Segment that consist of two 16U satellites (focus of this publication).
- Ground Segment that consist of the Ground station to communicate with the space segments, the mission control centre and the Payload Data Ground Segment (PDGS) that analyses the measurement data coming from the space segment and delivers the CH4/CO2 and NO2 concentration data to the TANGO users.
- The TANGO users are part of the TANGO science segment where also the TANGO E2E simulator is part of.
- The support segment that consist of all ground support and test equipment. This also includes a thermal vacuum facility for calibration of the space segments under operational conditions.

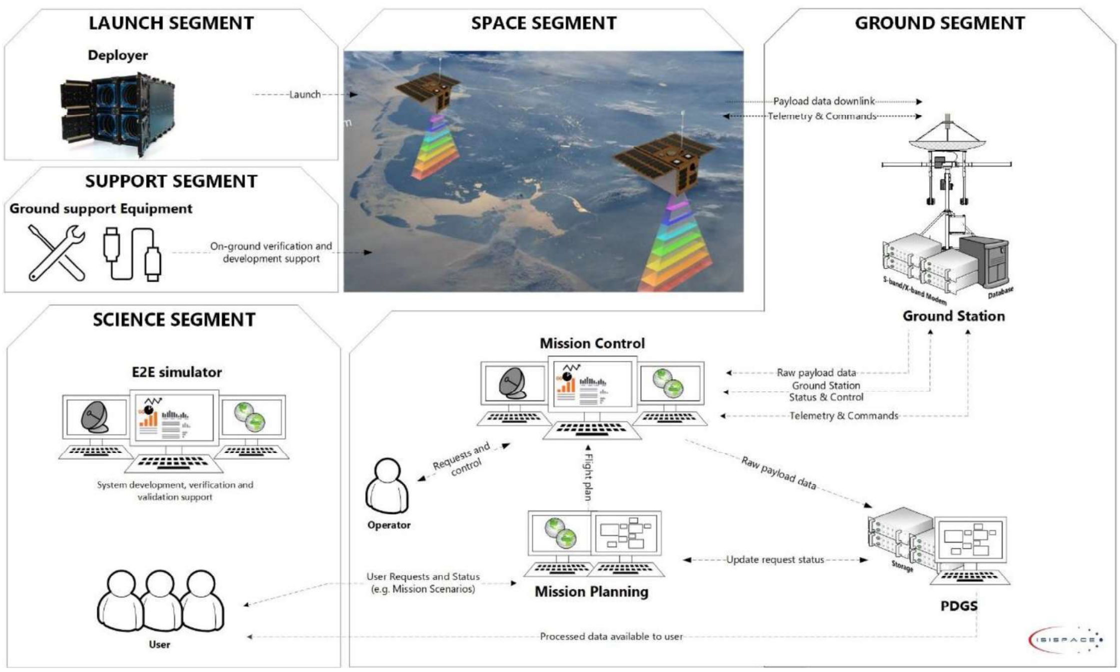

Figure 2-1: TANGO System architecture with major functional flows (courtesy of ISISPACE)

The TANGO space segment consists of two agile 16U CubeSat satellites (TANGO Carbon and TANGO Nitro) flying within one minute of each other. The agility of the CubeSat satellites will be used to access targets over a wide area by pointing of nadir as part of the standard operation and will be used to perform Forward Motion Compensation (FMC) manoeuvres to increase the observation time available for the scientific payloads.

Each satellite is equipped with a scientific payload consisting of an imaging spectrometer. TANGO Carbon will be equipped with an imaging spectrometer that measures the emission of CH_4 and CO_2, in the SWIR1 spectral band, while TANGO Nitro will be equipped with an imaging spectrometer that measures the emission of NO_2 in the visible spectral range. Both instruments are reflective push-broom spectrometers that use freeform mirrors to achieve a high optical performance, made almost entirely from aluminium, and will cover a 30-km swath from a 500-km altitude, with a spatial resolution <300 m in both across- and along-track.

In order to make a cost efficient space segment the architecture and design of the two satellites has been harmonised as much as possible. This approach has also been adopted for the two imaging spectrometers. They share a similar architecture and the design of the telescopes has been made identical.

In the rest of this paper the architecture and design of the two scientifical instruments will be discussed in more detail.

3. THE CARBON INSTRUMENT

The major design challenge of the Carbon instrument is to achieve a high etendue (and hence SNR), spectral resolution and spectral range in a relatively small instrument volume of 8U. Maturation of the Carbon instrument design was performed during the Risk Retirement Activities project phase [3][4]. The primary instrument parameters are listed in Table 3-1 and the optical design shown in Figure 3-1.

The instrument consist of a telescope and a spectrometer, separated by a slit. The silicon bandpass filter BP1 at the entrance of the telescope limits the wavelength range seen by the instrument to 1560-1700 nm range. The f/4 telescope is a conventional field-biased TMA consisting of hyperboloidal, ellipsoidal and spherical mirrors. Light from the slit is collimated by the collimator, CM1, dispersed by the planar reflective grating and imaged onto the FPA at f/1.9 by the three imager mirrors IM1, IM2 and IM3. The collimator and imager mirrors are freeform.

The alignment philosophy for the Spectrolite family of instruments requires relatively tight manufacturing tolerances (in the order of 20 µm) in order to minimize the duration and cost of the alignment phase. Such manufacturing tolerances are readily achieved at TNO, most recently in the manufacture of the Copernicus Sentinel 5 telescopes (TSBOA) and UV1 spectrometer. With these tolerances for TANGO Carbon, we find that only the first order aberrations of pointing and defocus require correction during the alignment phase. Alignment of the TANGO Carbon instrument therefore proceeds as follows. First, the instrument is assembled on manufacturing tolerances. Defocus in the telescope is measured and corrected by shimming TM2. Then, defocus in the spectrometer is measured and corrected by shimming IM2. Finally the lateral (and potentially clocking) alignment of the detector is corrected.

The mirrors in TANGO Carbon will be manufactured by single-point diamond turning (SPDT) followed by magneto-rheological finishing (MRF). It is well-known that SPDT is sensitive to local temperature oscillations during manufacturing that introduce periodic slope errors on the optic. These slope errors have a negative effect on optical performance. The amplitude and spatial period of these slope errors is dependent on multiple factors such as the size of the optic, the temperature sensitivity of the SPDT machine etc. For TANGO-sized mirrors produced at TNO, the spatial periods are on the order of 1 mm. The impact of these midspatial frequency errors on the optical performance has also been modelled and included in the performance analysis of the TANGO Carbon instrument

More details of the Carbon instrument optical design, tolerances analysis, straylight analysis and STOP analysis can all be found in [3].

During the conceptual design phase, three potential detectors were selected for the Carbon Instrument. Dedicated test campaigns to characterize these devices (two InGaAs devices and an alternative custom-doped 1.8µm cut-off HgCdTe device) were performed by SRON, see [5] for more details. The selected detector, the Snake SW from Lynred underwent TID radiation testing at the Co60 facility at ESA-ESTEC and showed compliance to the End-of-Life performance requirements.

Table 3-1 Summary of the TANGO Carbon instrument parameters

Parameter	**Unit**	**Value**	**Remark**
Nominal orbit height	km	500	
Swath	km	30	Across Track FOV = 3.4°
Spatial resolution at Nadir	km	0.3	Defined at System Integrated Energy ≥ 0.7
Spectral range	km	1590-1675	
Spectral resolution	km	≤ 0.50	ISRF FWHM. Spectral oversampling > 2.7
Average SNR	-	≥ 270	At L=3.16E+12 photons/(sr cm2 nm s)
Volume	U	8	400 mm × 200 mm × 100 mm
Mass	kg	< 8.5	Including margin

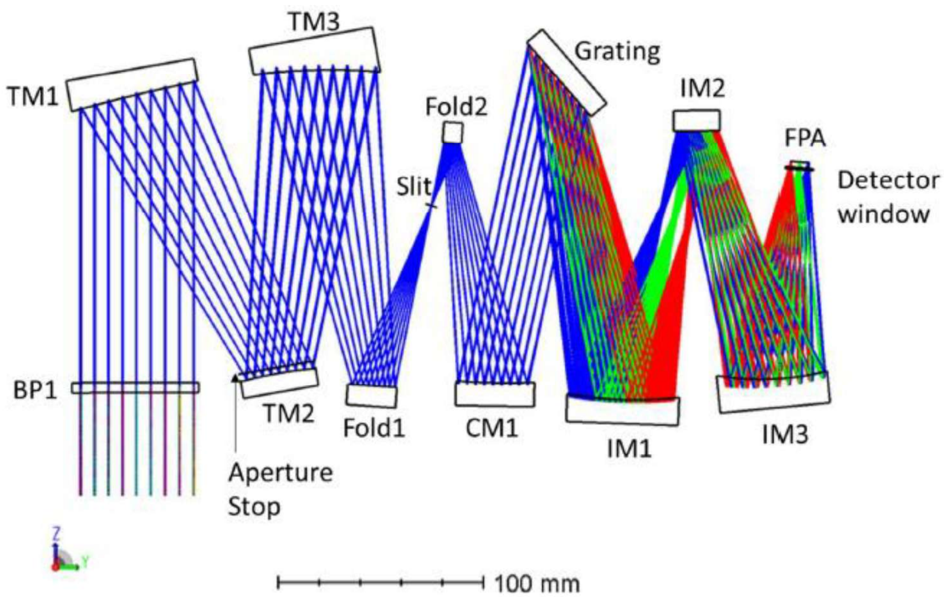

Figure 3-1 Optical design of the TANGO Carbon instrument

The mechanical design of the Carbon instrument is based on TNO's Spectrolite instrument design. A box structure is chosen which meets the necessary strength and stiffness requirements when the instrument is in an assembled state. A solid block of Aluminum 6082 T651 is milled-out and passivated. Using the intended mirror openings, chambers are milled out to make space for the light path envelope whilst creating a labyrinth blocking straylight. The components (mirrors assemblies, grating assembly, BP1 assembly, ect…) are bolted onto the housing, positioned with shims, reference pins and gauges. In order to ensure the stability needed to meet the stringent optical performance requirements, the instrument is actively kept at a fixed temperature near 20°C.

The instrument is isostatically suspended to the spacecraft structure by six titanium (low conductive) struts, which are capable of damping external vibration loads. Two of these struts can be seen on the left side ofFigure 3-2. The orthogonal orientation of the struts, adopted from the Spectrolite design, relaxes the assembly tolerances and reduces the instrument pointing error over the thermal range. The TNO design damped struts are 3D printed Ti with rubber injected in them and are identical to the struts of TNO's SmallCAT optical communication terminal currently flying on NorSat-TD. A cross-section of one of the struts is shown in Figure 3-3, where the viscoelastic damping rubber material is rendered in pink. The used viscoelastic rubber is a SCVBR rubber which is developed for use in situations where a low out-gassing characteristic is required. The damped struts are designed according to design-principles that are patented by TNO. These design-principles enable a strut-design with high stiffness, strength and outstanding damping performance. Finite

Element simulations predicted an instrument damping between 6 and 10% for the first six global eigenmodes of the TANGO instrument. Note that a similar mechanical design without damping struts would have a damping ratio of 1% or less. Amplification of the dynamics of the TANGO instrument is thus significantly reduced by the utilization of damped struts.

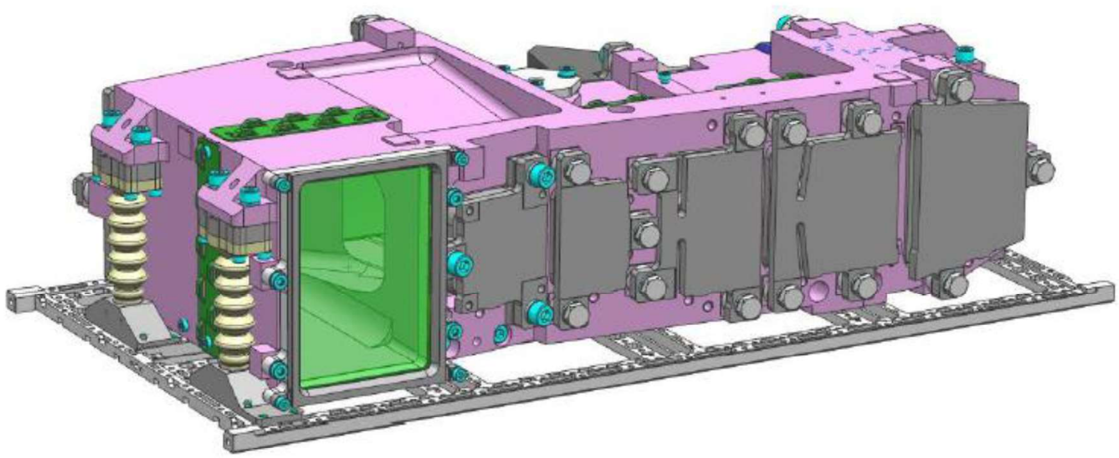

Figure 3-2: Mechanical design of the Carbon instrument

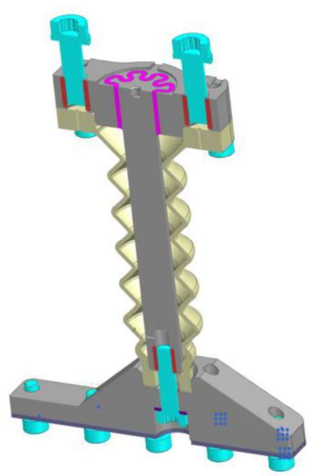

Figure 3-3 Cross-section of the damped strut

From the consolidated instrument design, a Structure and Thermal model (STM) of the Carbon instrument was built during the Risk Retirement Activities phase of the project. The housing, damped struts, mirror and BP1 were fully representative with only the optical coatings missing. The grating assembly, slit assembly and camera were replaced by mass dummies. To simulate the thermal loads of the camera, GSE heaters were added.

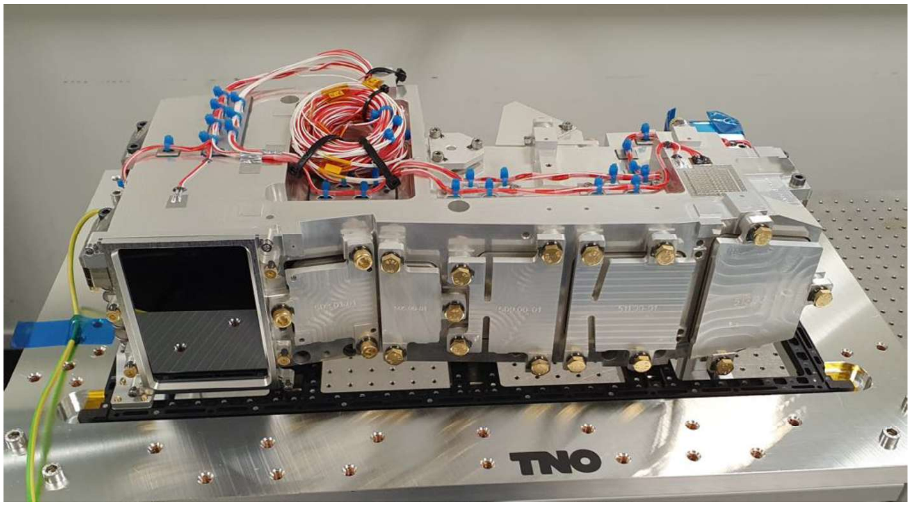

Figure 3-4: Carbon instrument STM

In order to ensure the accuracy and reliability of the Carbon instrument Finite Element Model (FEM), a resonance survey test was conducted on the STM. The objective of this survey was to validate the FEM predictions by comparing them with experimental results obtained through measurements of accelerations in three directions. The measured data was then transformed into transfer functions for further analysis and model tuning.

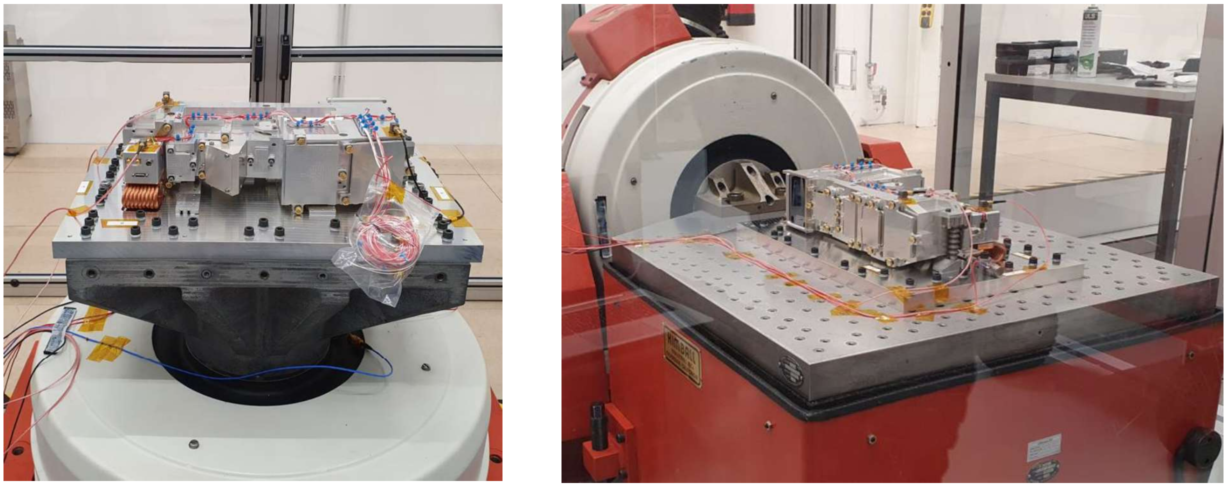

Figure 3-5: Carbon Instrument STM during the resonance survey

The damping performance of the Carbon instrument is derived from the transfer functions. The damping performance observed on the STM was even better than predicted with the FE model. The FE model for damping predictions is set up worst-case scenario by assuming that only the rubber material in the struts provides the damping properties. In reality however, also other characteristics of the instrument contribute to the damping performance, like the friction at bolted interfaces. The experimentally derived damping performance provide confidence to use the damped struts to safeguard the TANGO instrument against launch loads by amplification of the instrument dynamics.

The instrument STM was subsequently integrated into the spacecraft STM, verifying the interfaces between them. The combined system underwent launch loads test, thermal balance test and micro-vibration test. These environmental tests performed by ISISPACE have verified the structural integrity of the instrument design. The lowest eigenfrequency is well above the assigned threshold and the structure will survive quasi static, since, random vibration and thermal survival loads.

4. THE NITRO INSTRUMENT

Following the proven Carbon instrument design concept presented above, the TANGO Nitro instrument is designed to be as identical as possible, albeit with a slightly different spectrometer configuration and a different camera. Preliminary optical and mechanical design and analysis are in progress as a starting point for the upcoming mission implementation phase, the primary parameters of which can be found in Table 4-1.

Since the spatial resolution and FOV requirements are the same for both Nitro and Carbon instruments, the same telescope and slit design can be used. The Nitro instrument requires a smaller etendue than the Carbon instrument, which means that -in principle - the clear aperture of the telescope mirrors could be made smaller. For cost and manufacturing efficiency however, it is chosen to keep all telescope mirrors the same between the two instruments. Instead only the size of the rectangular aperture stop will be reduced. Obviously, all coatings are different from the Carbon instrument.

Due to the difference in etendue, the difference in grating design and the difference in detector geometry the Nitro spectrometer design varies from that of the Carbon instrument. The generic layout is the same: after the slit the light is collimated by a single free-form mirror, CM1, then dispersed by a reflective planar grating. An imager consisting of three free-form mirrors IM1, IM2, and IM3 focuses the light onto the CMOS detector. The overall spectrometer is a bit smaller than the Carbon equivalent.

Because the design does not include a polarization scrambler, the polarisation sensitivity of the instrument must be minimized to limit the bias errors on the retrieval of NO2 and cloud information. This especially imposes strict requirements on especially the grating performance. The chosen grating is an “industrial grade” holographic blazed grating from Carl Zeiss with a line density of 1500 l/mm, an angle-of-incidence (AOI) of 35°, and uses the -1 order. A prototype grating has been manufactured in the Risk Retirement Activities phase of the project and its performance was characterized by Carl Zeiss and by ESA TEC-QEE. With these results, an end-to-end retrieval simulation was performed by KNMI to confirm that the grating performance is acceptable.

Table 4-1 . Summary of the TANGO Nitro instrument parameters

Parameter	**Unit**	**Value**	**Remark**
Nominal orbit height	km	500	
Swath	km	30	Across Track FOV = 3.4°
Spatial resolution at Nadir	km	0.3	Defined at System Integrated Energy ≥ 0.7
Spectral range	nm	405-490	
Spectral resolution	nm	≤ 0.6	ISRF FWHM. Spectral oversampling > 2.3
Average SNR	-	≥ 400	At L=1.70E+13 photons/(sr cm2 nm s)
Volume	U	8	400 mm × 200 mm × 100 mm
Mass	kg	< 8.5	Including margin

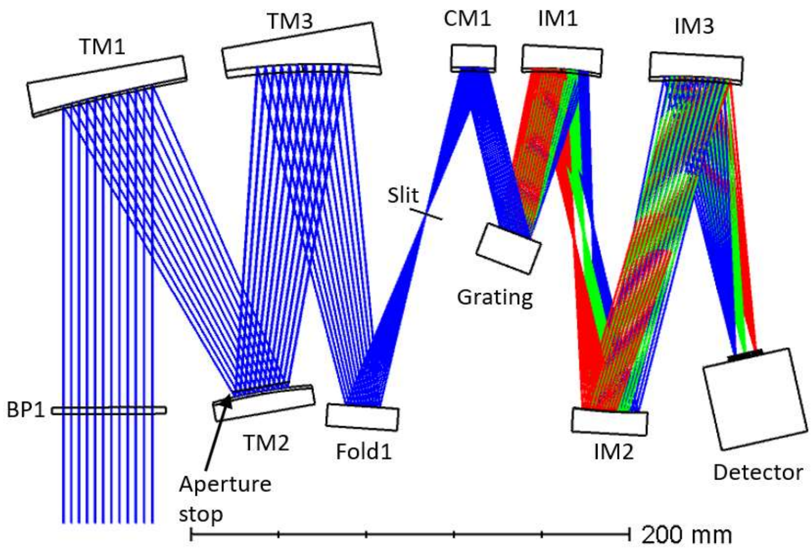

Figure 4-1: Preliminary optical design of the TANGO Nitro instrument

The baseline camera selected for the Nitro instrument is a commercial-off-the-shelf 3DCM800 Space Camera Head from 3D Plus with a 4096x3000 pixel, 3.45µm-pitch CMOS sensor. It integrates several built-in features such as subsampling, Region-Of-Interest readout, multiple bit-mode. The pixels are pre-binned on the camera FPGA before being send to the Payload Data Handling Unit of the platform. From these pre-binned images, two data products will be generated: one with a 300m ground resolution and a high spectral resolution (the NO2 science product) and one with a higher spatial resolution and a reduced spectral resolution (for cloud coverage measurement).

The preliminary mechanical design of the Nitro instrument is shown in Figure 4-2. The telescope side is identical to the TANGO Carbon instrument, while the spectrometer side is a bit smaller. All mirrors and the grating are mounted to the housing in the same way as the Carbon instrument. The same damping struts are used to mount the housing onto the platform and the active thermal control is also identical to that of the Carbon instrument.

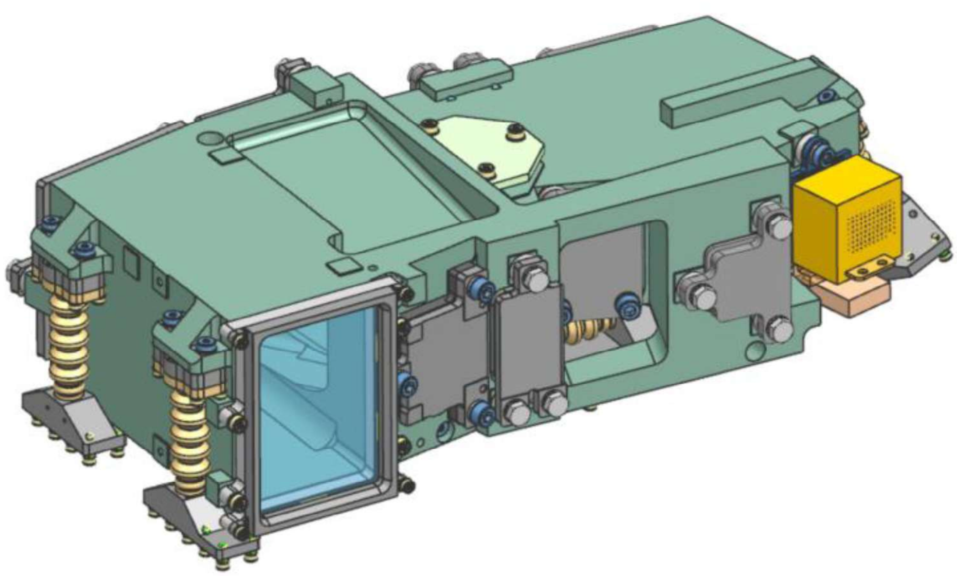

Figure 4-2: Preliminary mechanical design of the TANGO Nitro instrument

5. OUTLOOK

This paper has introduced the current status of the TANGO instruments, which are still under development. Currently, the project is approaching towards the implementation phase of the TANGO mission. Some of the design and development work has been initiated earlier in 2024; the main focus of these activities is to increase the design maturity of the Nitro instrument to the same level as for the Carbon instrument. The design, development and testing of the two instruments will be carried on in parallel during the mission implementation phase to benefit from the synergies that exist between them. The TANGO mission implementation phase is planned to be completed in three years until launch and will result in the capability to measure a significant portion of global CO2 and CH4 emissions at facility level, supporting climate control policies.

ACKNOWLEDGEMENTS

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