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Development of Spectrometers for the TANGO Greenhouse Gas Monitoring Missions

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ABSTRACT

The current paper introduces the Twin ANthropogenic Greenhouse Gas Observers (TANGO) instruments and mission. The purpose of TANGO is monitoring and quantifying greenhouse gas emissions, with a focus on characterizing emission sources down to the level of individual facilities. The TANGO mission was developed for the ESA-Scout program by a consortium consisting of ISISpace, TNO, SRON and KNMI. It consists of two agile CubeSat satellites that fly in tandem, with less than 1 minute between observations of the same target, each satellite equipped with a spectrometer of the TNO Spectrolite family of instruments that observes a different part of the spectrum. TANGO-Carbon measures emission of CH_4 and CO_2 in the SWIR1 spectral band. TANGO-Nitro measures emission of NO_2 in the visible spectral range. The Nitro instrument has a multifunctional role, using the NO_2 measurements to improve the detection of (anthropogenic) CO_2 plumes, deriving historic CO_2 emission trends based on available global NO_2 observations, and quantifying the possible CO_2 contribution in mixed CH_4-CO_2 sources. Each TANGO instrument fits in an 8U volume (on a 16U platform) and are all-aluminium, reflective pushbroom spectrometers covering a 30-km swath from a 500-km altitude, with a ground sampling distance of 300 m × 300 m. In this paper we will present the mission, the shared instrument concept, as well as the design and performance of both Carbon and Nitro instruments.

Keywords: small satellites, CubeSat, spectrometer, free-form mirror, greenhouse gas emissions.

1. INTRODUCTION

Climate change is one of the most urgent problems of our time. It can cause shifting weather patterns that threaten food production, rising sea levels that increase the risk of major floods, and cause refugee and immigration flows. In the year 2015, within the United Nations Framework Convention on Climate Change (UNFCCC), the Paris Agreement[1] was signed by 195 countries agreeing to combat climate change and to accelerate and intensify the actions for a sustainable low carbon future. The main objective of this agreement is to strengthen the global response to climate change and to deploy greenhouse gas mitigation strategies to keep the global temperature rise this century well below two degrees Celsius above pre-industrial values. In the last century, the global mean temperature rose continuously, mainly due to the anthropogenic emission of gases. The inevitable management of global warming mitigation efforts require solid and continued measurements of key parameters like the anthropogenic emission of the two most important greenhouse gases CO_2 and CH_4.

A significant portion of the manmade emissions of CO_2 and CH_4 come from a limited number of sources. For example, about 2.5% of the power plants in Europe are responsible for 40% of the sector's emissions. Similarly, studies on oil and gas producing and processing assets show that only about 7% of their sources are responsible for 40% of the sector's total methane emissions[2-4]. To date, there is significant uncertainty about the emission strength, and sometimes even location, of these sources. Therefore, data on these emissions and the changes over time are urgently needed in order to collect evidence that policy measures to combat climate changes are effective.

TANGO (Twin ANthropogenic Greenhouse gas Observers) is a satellite observatory that will monitor moderate to strong emissions of the greenhouse gases methane (CH_4) and carbon dioxide (CO_2) at the level of individual industrial facilities and power plants. TANGO will provide independent emission data that will allow scientists, policy makers and industry

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to monitor the emissions of a significant portion of the manmade CO_2 (44% threshold, 66% goal) and CH_4 (68% threshold, 75% goal) emissions from the power sector and industrial sites.

This paper will first describe the TANGO mission concept and shared instrument concept. Next the optical design and performance of the Nitro and Carbon instruments are discussed, to show how key issues such as high SNR from a small volume, athermal design, and polarization sensitivity have been addressed.

2. TANGO MISSION

2.1 Mission concept

The TANGO mission is an end-to-end science solution consisting of data products, data processing, instruments, satellite platforms, ground-segment, launch and in-orbit commissioning. It was developed for the ESA-Scout program by a consortium consisting of ISISpace, TNO, SRON and KNMI. TNO is in charge of the design and development of the two instruments, working closely together with SRON and KNMI that are responsible for the atmospheric science, and prime contractor ISISpace that delivers the platform. The current mission will act as a proof of concept that will illustrate the benefits of TANGO in terms of cost, scalability, high evolution speed of technology, rapid response to new measurements needs, data efficiency and mission resilience.

The TANGO concept was developed in order to allow the realization of a European satellite mission that can make targeted measurements of greenhouse gas emissions at facility level for selected areas with open data access at high spatial resolution and precision, and with a flexible mission operation concept for area selection.

The TANGO mission utilizes a pair of CubeSat technology-based satellites. Both spacecraft are equipped with one spectrometer instrument each, one configured to measure CH_4 and CO_2 (TANGO-Carbon), while the other is designed to measure atmospheric NO_2 (TANGO -Nitro). The spacecraft platform is highly agile to allow for the targeted monitoring of facilities and other ground targets. Both satellites will fly in a train with less than 1 minute between the two satellite's observations of the same target, increasing the symbiotic value of the mission. The goal is to quantify and monitor selected sources of greenhouse gas emissions at the level of individual facilities. To this end, TANGO measures:

- Carbon dioxide (CO_2) emissions with a threshold of $\geq$ 5 Mt/yr and goal of $\geq$ 2.5 Mt/yr, representing respectively about 44% and 66% of the annual global total CO_2 emission of the power sector.
- Methane (CH_4) emissions with a threshold of $\geq$ 10 kt/yr and goal of $\geq$ 5 kt/yr, representing respectively about 68% and 75% of the annual global total emissions of major industrial emitters including the oil & gas sector, coal mines, and landfills.
- Nitrogen dioxide (NO_2) column concentrations, which will improve the detection of CO_2 plumes, deriving historic CO_2 emission trends based on readily available global NO_2 observations, and quantifying the possible CO_2 contribution in mixed CH_4-CO_2 sources.

TANGO will be providing targeted observations. These targeted observations will be complimentary to the global observations of the Copernicus Sentinel 5-P (S5P), Sentinel 5 (S5) and CO2M missions. The unique contributions of TANGO will be:

- Its ability to monitor emission plumes at a spatial resolution of 300 m × 300 m.
- Its possibility to extend observation times over targets by means of the innovative Forward Motion Compensation (FMC) technology (from 4 s to 12 s for a 30 km x 30 km scene).
- The resulting high precision on quantified emission fluxes, which will be a factor of two better than CO2M.
- Its ability to measure CO_2, CH_4 and NO_2 at the level of individual industrial facilities and power plants.
- Its flexibility as a mission operation boosting the yield of useful observations.
- Its open data policy for making emission data and all underlying data freely available.
- The CubeSat technology and distributed observations mean TANGO can be readily extended to a constellation of satellites that jointly provide a wide range of atmospheric monitoring tasks.

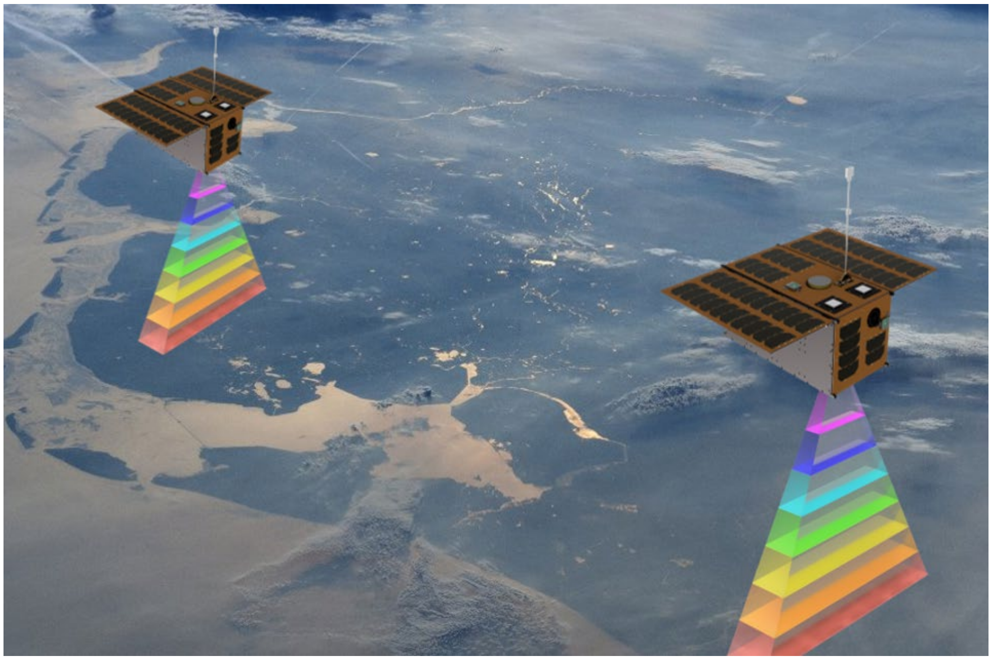

Figure 1. Artistic impression of the twin spacecraft flying in formation above the Netherlands

TANGO provides the proof of concept of a novel type of Earth observation mission for monitoring the composition of the atmosphere (see Figure 1 for an artistic impression). It enables targeted measurements of areas of specific concern, complementing observations of European Copernicus missions with a full global coverage. The mission concept of TANGO is of value because significant capital investments and development timelines are required to meet the accuracy, precision and spatial detail of satellite instruments that can provide (daily) full global coverage for the monitoring of emissions. However, the modular CubeSat concept of TANGO allows for a rapid and cost effective development. Moreover, many urgent scientific issues in atmospheric monitoring do not require global coverage. The quantification of anthropogenic hot spot emissions of greenhouse gases is one example of this.

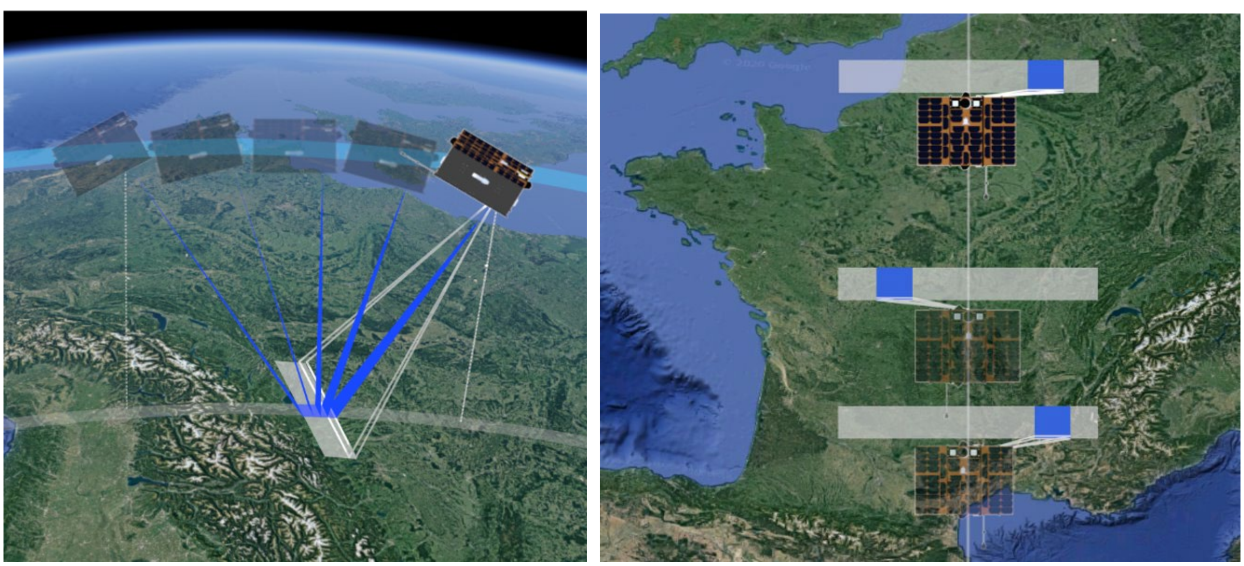

Figure 2. TANGO agile observation modes including Forward Motion Compensation (left) to increase the integration time and "boost" the instrument Signal to Noise Ratio and Agile Targeting (right) to allow the high resolution instrument to access multiple greenhouse gas emission sources during a single pass.

Satellites provide a unique opportunity for the independent and frequent monitoring of such emissions at a global scale. The TANGO mission will demonstrate that these sources can be monitored using compact scientific instruments that have lower level of requirements than the ones used in conventional (wide swath) missions. TANGO will allow for the monitoring of 150-300 locations in four days by means of the two satellites that are part of this demonstration mission.

The mission will use agile ISISpace 16-Unit satellites based on CubeSat technology, which pioneer the technology of Forward Motion Compensation (FMC) on this size of satellite platforms. This will allow the TANGO satellites to track their targets and extend observation times by a factor of 3 or more which has the advantage to enhance the signal-to-noise ratio and thus to reduce the error of emission quantification significantly (see Figure 2). The use of TNO Spectrolite instruments, which can readily be reconfigured to measure different trace gases, in combination with CubeSat technology-based platforms, leads to faster development times and lower mission costs.

2.2 Instrument Concept

The imaging spectrometers used in TANGO-Carbon and TANGO-Nitro are of the TNO Spectrolite family of instruments[5-7]. These are all-aluminium push broom spectrometers that provide a high performance in a modest volume due to the use of free-form optics. The motivation to use the Spectrolite instrument as the baseline for TANGO can be summarized as below.

- Spectrolite was developed by TNO based on the legacy of the highly successful TROPOMI instrument used in the operational Sentinel 5p mission (S5p).
- Significant heritage exists for retrieval methods from other missions (like Sentinel 5p) which can be used for Spectrolite, which positively impact the maturity of the science of the TANGO mission.
- Spectrolite was developed with the aim to be readily configurable to measure different trace gases, which is a key point for TANGO because it allows the TANGO-Nitro and TANGO-Carbon instruments to be developed based on the same family of instruments, saving development cost and time as well as capturing of lessons learned and heritage from the various design iterations.
- The use of free-form mirror technology in Spectrolite design makes it a relatively compact instrument that has the potential to obtain high performance, which fits the mass and volume constraints of this CubeSat mission and the relatively stringent requirements on signal-to-noise needed for a mission that measures trace gases.

Implementing this heritage results in both TANGO instruments that are reflective pushbroom spectrometers covering a 30-km swath from a 500-km altitude, with a ground sampling distance (GSD) of 300 m in both Across Track (ACT) and Along Track (ALT). Achieving this high spatial resolution with an adequate SNR was a main design driver, necessary to achieve the mission goal of monitoring emissions from individual facilities. TANGO-Carbon targets SNR>300, and TANGO-Nitro targets SNR>400 (exact values depend on the forward motion compensation factor and the solar zenith angle).

Both instruments use the same TMA telescope design with off-axis conics (albeit with different apertures/f#s), helping to save manufacturing and integration costs. The spectrometers also use a similar architecture, with free-form collimator and imager mirrors. Each instrument fits in an 8U volume, on a 16U platform. Due to this small satellite platform with limited potential to control the thermal environment, an inherently athermal design is preferred. This is achieved by designing these instruments to consist almost entirely of aluminium and hence they are almost insensitive to thermal offsets.

3. NITRO INSTRUMENT

3.1 Optical Requirements

The instrument requirements for TANGO-Nitro relevant to the optical design are given in Table 1. We note that the science sample etendue requirement is more relaxed than for the Carbon instrument by nearly a factor of 2 and can be reached without the use of forward motion compensation (FMC). The spectral range is chosen so as to derive both the total tropospheric column of NO_2 as well as determine cloud information.

Table 1. TANGO-Nitro instrument requirements relevant to the optical design.

Parameter	Unit	Value
Altitude	km	500
Swath	km	30
ACT GSD at nadir	km	0.3
ALT GSD at nadir	km	0.3
Minimum wavelength	nm	405
Maximum wavelength	nm	490
Spectral resolution	nm	0.6
Spectral oversampling	-	2.3
Science sample etendue	mm^2sr	3.5E-4
Instrument volume	U	8

3.2 Optical design

The optical design of the TANGO-Nitro instrument is depicted in Figure 3. The instrument is an imaging spectrometer, composed of a telescope that images the light from Earth onto a slit and a spectrometer that images the spectrally dispersed light from the slit onto a CMOS detector. Light enters the instrument through the first of the two bandpass filters, BP1. The second bandpass filter BP2 is placed just before the slit and together these filters limit the wavelength range seen by the instrument to ~400 nm to 500 nm. In principle a single filter can suffice, but due to more stringent straylight requirements expected for the Nitro instrument than for the Carbon case, two filters are chosen for the current baseline to have more control over out-of-band rejection, albeit at the potential cost of more ghost straylight.

The telescope consists of three powered mirrors TM1, TM2 and TM3, and a planar folding mirror Fold1. The telescope is a conventional field-biased, Korsch type three-mirror anastigmat (TMA), consisting of two conic sections and a sphere. The telescope is telecentric at the image plane at the slit, which functions as the field stop in both the ALT and ACT directions. It also acts as an aperture separating the telescope and spectrometer subsystems of the instrument and thus limits straylight. The rectangular aperture stop for the complete instrument is a physical aperture located close to TM2. Fold 1 is included to fold the back focal distance of the TMA within the 8U envelope.

As mentioned in Section 2.2 and shown in Table 1 and Table 3, the spatial requirements (swath and GSD in both ACT and ALT directions) are the same for the Nitro and Carbon instruments, so it is possible to use the same telescope design for the two instruments. Due to the difference in required etendue, the apertures and f# will be different (nearly a factor 2 difference in entrance pupil area), but the same mirrors and slit can be used. This approach fits well with the CubeSat philosophy, allowing to save time and costs on the optical and mechanical design, manufacturing, and integration. Because of the more stringent performance requirements for the Carbon instrument, the telescope was designed for that purpose first, then adapted to suit the Nitro requirements.

After the slit, 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 layout and description shows that two elements from larger instruments specialized in global coverage such as Sentinel 5 are omitted in TANGO: a polarization scrambler and slit homogenizer. Although these choices reduce certain performance metrics, those losses are acceptable due to the lower complexity and costs for design, manufacturing and integration. This is exactly the main motivation for the TANGO mission: to demonstrate a new way of monitoring the composition of the atmosphere, where targeted viewing and agile platforms allow for lower instrument performance while meeting the requirements of the science product.

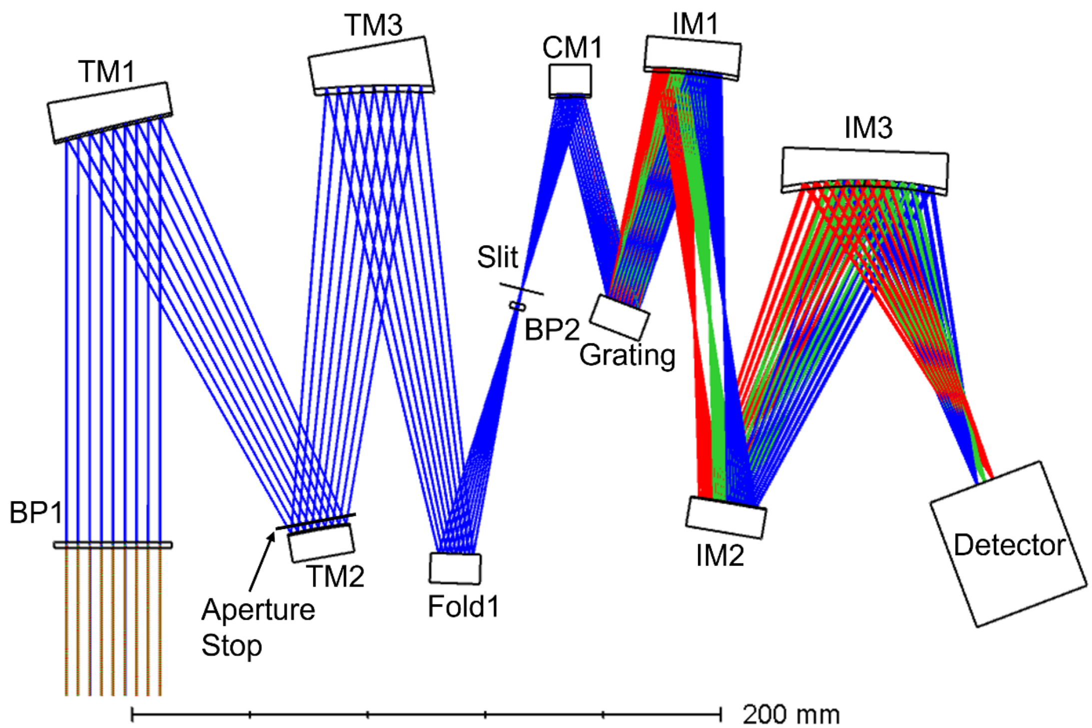

Figure 3. Optical design of the TANGO-Nitro instrument

Omitting a polarization scrambler does place certain requirements on the optical design, mainly to limit the polarization sensitivity of the entire instrument. The largest contributor is typically the reflective grating, in part because such gratings can exhibit strong polarization dependencies, including effects that are known as Rayleigh and Wood's anomalies[8,9]. Thanks to a fruitful collaboration with Zeiss, characterization and optimization of the grating performance was achieved, leading to a feasible solution.

A summary of the preliminary optical performance of the TANGO-Nitro instrument most relevant to the higher-level requirements is given in Table 2. A detailed tolerance analysis is ongoing, so these values only include an estimate for the impact of tolerances and are based on worst case (geometrical) results from the nominal design, but do show that requirements are met with varying margins to spare.

Table 2. Summary of the optical performance of the TANGO-Nitro instrument

Parameter	Unit	Value	Remark
Spatial resolution at System integrated energy of 0.7	m	285	Requirement = 300m
Spectral resolution	nm	0.597	Requirement = 0.6 nm. Slit size/dispersion @ detector
SNR	-	>400	SZA = 0°, albedo = 0.05, No FMC

4. CARBON INSTRUMENT

4.1 Optical Requirements

The instrument requirements for TANGO-Carbon relevant to the optical design are given in Table 3. We note that the science sample etendue requirement leads to an instrument that is able to achieve the required SNR with reasonable values of forward motion compensation (FMC) within the envelope constraints. Despite the use of FMC to increase dwell time and hence boost SNR, the major design challenge engendered by the requirements in Table 3 is still to achieve a large aperture in a relatively small instrument volume. As explained above in Section 2.2, these challenges are overcome by leveraging technology developed by TNO in its Spectrolite family of instruments: the use of free-form mirror technology leads to relatively compact instruments that have the potential to obtain high performance, while also consisting almost entirely of aluminium, which leads to a design that is inherently athermal and almost insensitive to thermal offsets. The TANGO-Carbon design therefore fits the mass and volume constraints of this CubeSat mission and the relatively high requirements on signal-to-noise needed for a mission that measures trace gases.

Table 3. TANGO-Carbon instrument requirements relevant to the optical design.

Parameter	Unit	Value
Altitude	km	500
Swath	km	30
ACT GSD at nadir	km	0.3
ALT GSD at nadir	km	0.3
Minimum wavelength	nm	1590
Maximum wavelength	nm	1675
Spectral resolution	nm	0.45
Spectral oversampling	-	3.0
Science sample etendue	mm^2sr	6.9E-4
Instrument volume	U	8

4.2 Optical design

The optical design of the TANGO-Carbon instrument is depicted in Figure 4. The instrument consists of a telescope and spectrometer, separated by a slit. Light from Earth enters the instrument through the silicon bandpass filter, BP1. This bandpass filter limits the wavelength range seen by the instrument to ~1560 nm to 1700 nm. Wavelengths below ~1000 nm are absorbed by the silicon substrate. The detectors considered for TANGO-Carbon are insensitive to wavelengths above ~1900 nm.

The telescope is a field-biased TMA, as already described previously in section 3.2. Except for the aperture sizes and bandpass filters, the TANGO-Nitro telescope and slit are the same as for the TANGO-Carbon shown below.

Following the Spectrolite heritage, both instruments also utilize a similar spectrometer architecture. Light from the slit is collimated by the collimator, CM1, dispersed by the planar reflective grating and imaged onto the FPA by the three imager mirrors IM1, IM2 and IM3. The collimator and imager mirrors are free-form, which permits high performance in a small volume compared to conventional optics. The TANGO-Carbon spectrometer also contains one additional planar folding mirror, Fold2, placed after the Slit to maintain the spectrometer within the 8U envelope. The entrance window to the detector Dewar is also included in the spectrometer design. Larger apertures, longer focal lengths in the spectrometer and a Dewar-cooled detector make the Carbon instrument more challenging to fit into the envelope than the Nitro instrument.

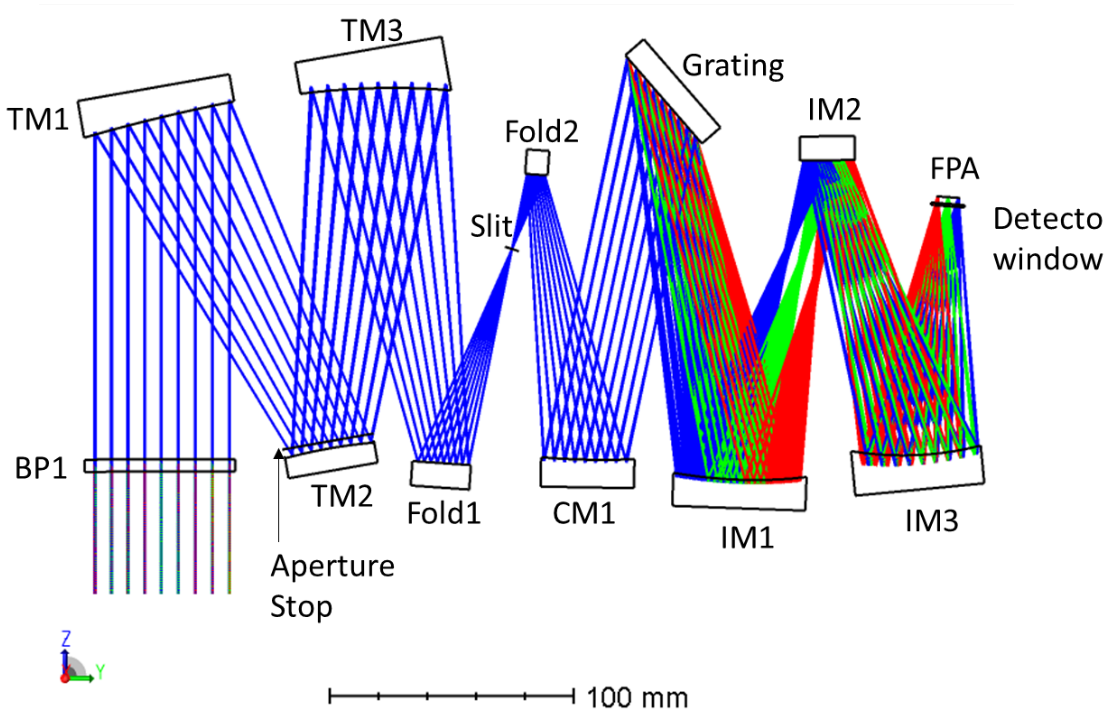

Figure 4. Optical design of the TANGO-Carbon instrument

The optical performance of the TANGO-Carbon instrument most relevant to the higher-level requirements is given in Table 4. These values include tolerances from optical and mechanical manufacturing (including the impact of mid-spatial frequency surface errors) and are reported after a (simulated) alignment procedure. The reported values are the maximum over all fields and wavelengths and are reported at the 2-sigma level following Monte Carlo analysis. The values therefore represent the worst case that we expect to achieve; in practice the performance is expected to be superior to these values.

Table 4. Summary of the optical performance of the TANGO-Carbon instrument

Parameter	Unit	Value	Remark
System integrated energy at 300 m spatial resolution	-	0.75	Requirement = 0.7
Spectral resolution	nm	0.455	FWHM of ISRF
SNR	-	355	SZA = 70°, albedo = 0.15, FMC = 3

4.3 Mechanical design

An impression of the mechanical housing of the TANGO-Carbon instrument can be seen in Figure 5. The mechanical design is also based on the Spectrolite philosophy. Mirrors and other optical features are mounted from the outside onto a box structure. The entrance aperture with the silicon bandpass filter can be seen on the front-left side. The instrument is iso-statically suspended to the spacecraft structure by six titanium (low conductive) struts, two of which can be seen on the left side.

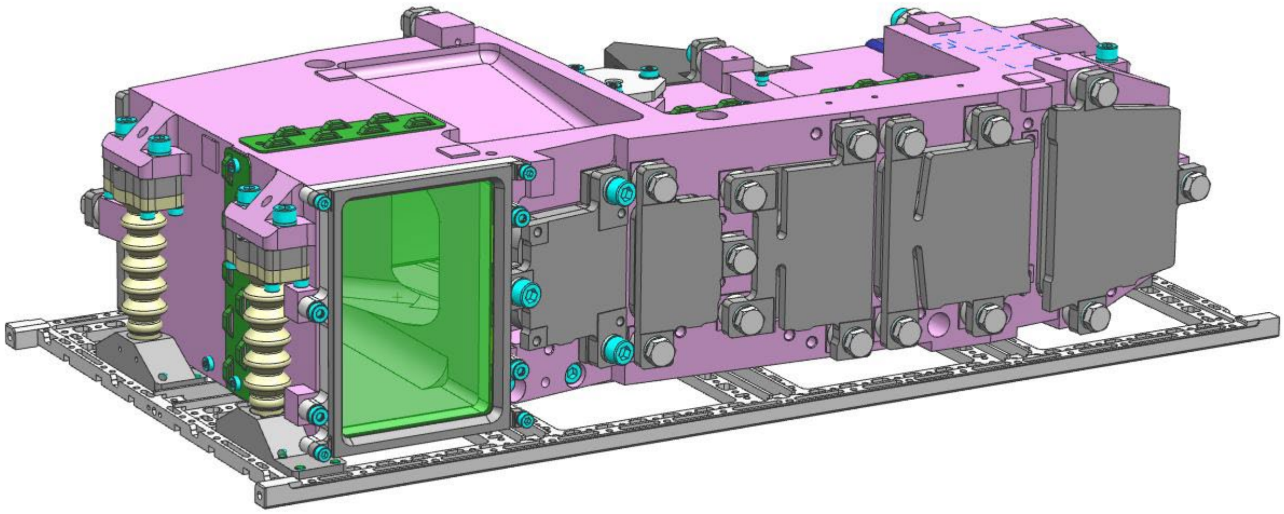

Figure 5. Mechanical housing of the TANGO-Carbon instrument

5. CONCLUSIONS

This paper introduces the TANGO mission, which has the purpose to monitor a significant portion of the manmade CO_2 and CH_4 emissions from individual facilities. The mission goals will be fulfilled by a pair of imaging spectrometers on separate agile CubeSat platforms, allowing them to track their targets and extend observation times. The Spectrolite heritage of the instruments has been explained, followed by an overview of the optical requirements, design and performance for Nitro and Carbon instruments. Although analyses are still ongoing, the two instruments show that they meet high-level requirements such as spatial resolution and SNR. Future work will detail end-to-end performance, manufacturing and integration, bringing the capabilities to monitor emissions from individual facilities much closer to reality.

6. ACKNOWLEDGMENTS

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