# AN OVERVIEW OF THE RISK RETIREMENT ACTIVITIES OF ESA'S CANDIDATE SCOUT MISSION TANGO

**A. Paškevičiūtė-Kidron [1], R. Windpassinger [1], A. Malavart [1], Z. de Groot [2], J. Strenge [2], I. Bustamante [2], N. Alpay Koc [3], B. de Goeij [3], E. Palombo [3*], E. van Schreven [3], P. Toet [3*], J. Day [3], B. Brenny [3], B. Ouwerkerk [3], M. Lemmen [3], G. Misiun [3*], E.V. Salcedo [3], R.R. Cooney [4], P. Tol [4], M. Klettke [4], I. Malysheva [4], J. Landgraf [4], M. van Hoek [5], J.P. Veefkind [4]**

*[1] ESA, European Space Agency / ESTEC, Keplerlaan 1, PO Box 299, 2200AG Noordwijk, The Netherlands, +31641377803, agne.paskeviciute@ext.esa.int*
*[2] ISISPACE , Innovative Solutions In Space B.V., Motorenweg 23, 2623CR, Delft, The Netherlands, +31152569018, z.degroot@isispace.nl*
*[3] TNO, Netherlands Organisation for Applied Scientific Research, Anna van Buerenplein 1, 2595DA The Hague, The Netherlands, +31888666212, nurcan.alpaykoc@tno.nl, *not employed at TNO anymore*
*[4] SRON Netherlands Institute for Space Research, Niels Bohrweg 4, 2333CA Leiden, The Netherlands, r.cooney@sron.nl*
*[5] KNMI Royal Netherlands Meteorological Institute, PO Box 201, 3730AE De Bilt, The Netherlands, +31615829809, pepijn.veefkind@knmi.nl*

## PAPER

TANGO (Twin ANthropogenic Greenhouse gas Observers) mission aims at identifying and quantifying moderate to strong anthropogenic $CH_4$ and $CO_2$ emission sources on an industrial scale. TANGO consists of two 16U CubeSats, TANGO Nitro and TANGO Carbon, flying in a loose formation. Each satellite will be equipped with a grating spectrometer instrument, with a swath of 30 km and a ground sampling distance (GSD) of 300 m.

TANGO underwent through a mission consolidation phase during the first cycle of ESA's Scouts, together with HydroGNSS, CubeMap and NanoMagSat. After the system consolidation study, further risk retirement activities were conducted on the following main areas: instrument technologies maturation, structural-thermal model (STM) development and testing, payload performance simulations. Both TANGO Carbon and TANGO Nitro instrument optical designs were further matured. The grating for TANGO Nitro was designed, manufactured and tested. An InGaAs SWIR detector for TANGO Carbon was selected after characterising both InGaAs and MCT detectors. The TANGO Carbon STM model, consisting of an instrument STM integrated in a representative satellite STM, underwent environmental testing. The test results were correlated with the results of detailed thermal and structural analysis. Data derived from detector characterisation and instrument performance simulation were integrated into an end-to-end payload performance simulator used for validating L2 product performance. Additionally, a cloud clearing AI algorithm was further developed for identifying and discarding cloudy pixels.

# 1 INTRODUCTION

The European Space Agency (ESA) launched the Scout initiative in 2019, introducing small budget research missions to complement Earth Explorers and have a rapid development cycle of 3 years from the start of implementation to launch. Twin ANthropogenic Greenhouse Gas Observers (TANGO) is a candidate Scout mission. TANGO underwent a system consolidation study phase from December 2019 until September 2020. It was then selected for further Risk Retirement Activities (RRA), initiated in late 2021 and concluded in early 2024.

The RRA was conducted by a consortium led by ISISPACE (NL) under an ESA contract. The consortium also includes TNO (NL), SRON (NL), and KNMI (NL).

This paper presents the work and results of the TANGO RRA, carried out by the industrial consortia.

## 1.1 MISSION CONCEPT

TANGO aims to identify and quantify moderate to strong anthropogenic $CH_4$ and $CO_2$ emission sources on an industrial scale. With high spatial resolution and high radiometric precision, TANGO aims to complement the Copernicus Sentinel-5 and CO2M missions. TANGO consists of two 16U CubeSats, TANGO Carbon and TANGO Nitro, flying in a loose formation. Both satellites will be orbiting Earth at approximately 500 km altitude, in Sun Synchronous Orbit (SSO). Each satellite will weigh approximately 27 kg. Both TANGO Carbon and TANGO Nitro platforms will be almost identical, featuring high performance AOCS systems and X-band transmitter for payload data downlink.

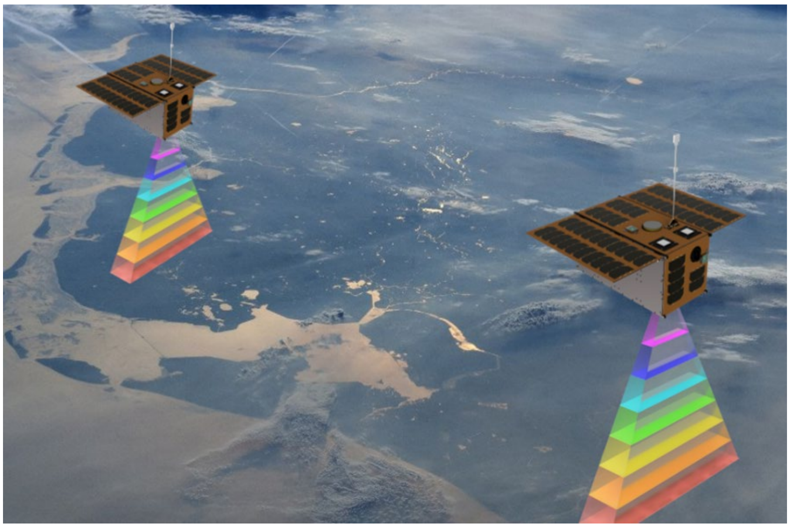

Figure 1. Artistic visualisation of TANGO Carbon and TANGO Nitro flying in loose formation, not to scale (credits: ISISPACE).

TANGO Carbon will detect and quantify the emissions of localised sources with detection limits of:

- ≥ 2.5 Mt/year (goal) and ≥ 5 Mt/year (threshold) for CO2;
- ≥ 5.0 kt/year (goal) and ≥ 10 kt/year (threshold) for CH4;

with a flux uncertainty smaller than 15%. TANGO Nitro detects atmospheric NO2 and provides information on clouds. NO2 measurements will be used to identify the plumes of combustion sources `(see Figure 2 below) and the NO2/CO2 ratio reveals information on the combustion process. Additionally, knowledge of the NO2/CO2 ratio can be used to derive historic trends in CO2 emissions from the NO2 data records of other satellite missions. Both satellites will have the capability to conduct forward motion compensation (FMC, Figure 3) and slewing manoeuvres. FMC is used to track targets, increasing the signal-to-noise ratio (SNR) and significantly reducing emission quantification errors, thus facilitating CO2 plume detection.

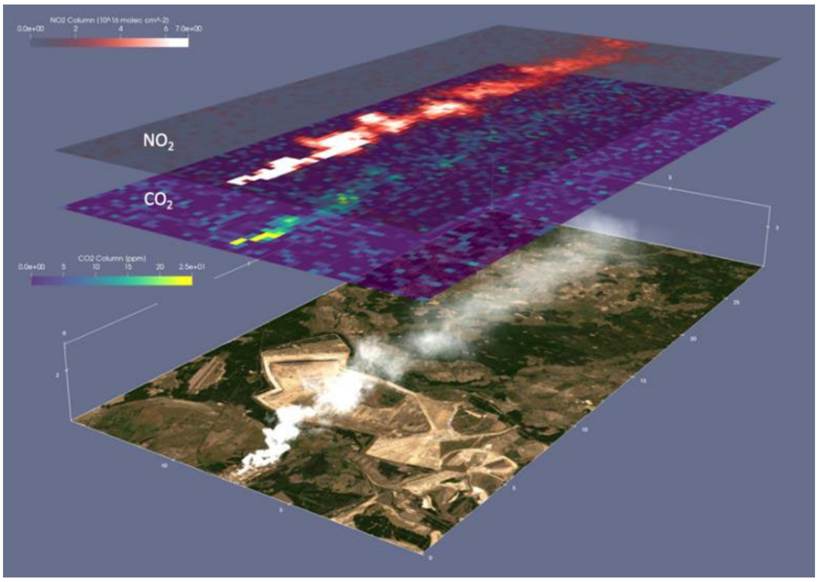


Figure 2. 3D simulation of a NO2 and CO2 emission plume of the Jänschwalde power plant seen by TANGO. The underlying surface reflectance is based on Sentinel-2 data. The CO2 and NO2 column concentrations include realistic signal-to-noise representations (credits: KNMI).

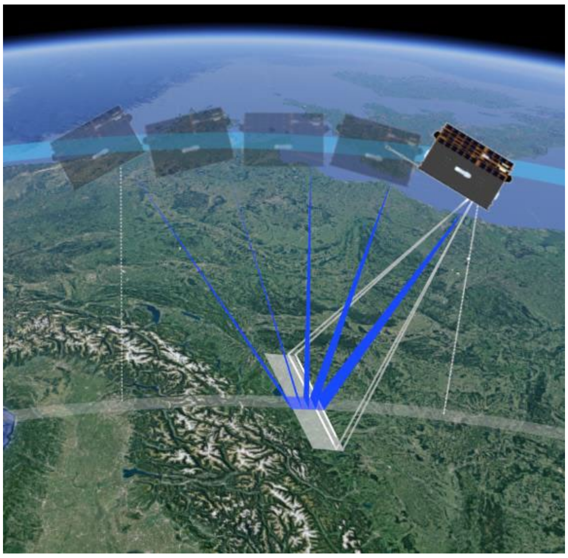

Figure 3. Artistic visualisation of TANGO spacecraft performing an FMC manoeuvre, not to scale (credits: ISISPACE).

Each satellite will be equipped with a grating spectrometer instrument, and feature a swath of 30 km and a ground sampling distance (GSD) of 300 m. TANGO Carbon focuses on measuring $CH_4$ and $CO_2$ emissions in a shortwave infrared (SWIR) wavelength band at 1.6 µm with 0.45 nm spectral resolution. TANGO Nitro retrieves information on $NO_2$ and on clouds in a visible wavelength band at 0.4 µm with 0.6 nm spectral resolution.

### 1.2 RISK RETIREMENT ACTIVITIES OVERVIEW

After a mission consolidation phase, in order to reduce technical and programmatic risks, specific activities were identified to mature the following main areas of the TANGO mission:

1. **Instrument technologies maturation**. This task focused on the optical design maturation of both spacecraft instruments, with special attention given to grating design and performance testing. A second focus was on the detector technology selection for the TANGO Carbon instrument.
2. **Structural-thermal model (STM) de-risking**. This task focused on structural and thermal model development and testing of a representative TANGO Carbon satellite STM, allowing to correlate the detailed thermal and structural analysis models, and de-risk mechanical and thermal interfaces.
3. **Payload performance simulations**. This task focused on the validation of the TANGO main L2 products performance, by including TANGO Carbon and TANGO Nitro design updates and test results in end-to-end performance simulations.

## 2 INSTRUMENT TECHNOLOGIES MATURATION

Instrument technology maturation task was focussed on the TANGO Carbon instrument due to its more complex design and more challenging thermal requirements. However, due to the similarities between TANGO Carbon and TANGO Nitro instruments, TANGO Nitro instrument had benefit from TANGO Carbon advancements.

The TANGO Carbon instrument optical design (by TNO), is shown in Figure 4 below. The instrument consists of a telescope and a 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. 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 high reflective coating (HR) is applied to all mirrors and the long-pass (LP) and band-pass (BP) coatings are applied to the silicon bandpass filter. The grating is designed as a single-order grating with a period (1.1 mm) that is close to the wavelength of the incident light. The efficiency and polarisation sensitivity of the grating are shown to meet the required performance.

The instrument is isolated from the spacecraft structure by the 6 damping struts (Figure 4, right image). These struts effectively dampen external vibration. The instrument is almost entirely aluminium, which makes it less sensitive to thermal offsets.

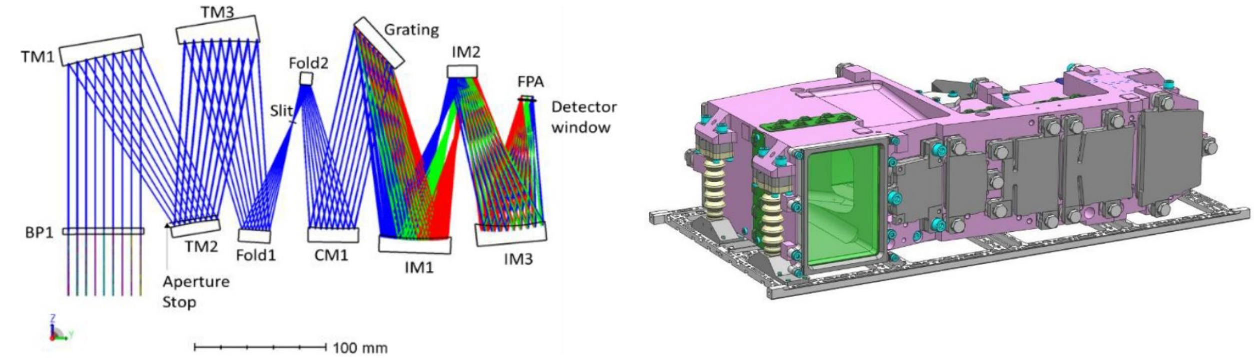

Figure 4. TANGO Carbon instrument design (credits: TNO).

TANGO Nitro instrument, also designed by TNO, is very similar to the TANGO Carbon instrument discussed above. It has the same number of elements, the same mounting of optical components, and the same interface with the platform concept. The coating of the TANGO Nitro mirrors is different to TANGO Carbon.

A grating for each instrument was designed. TANGO Nitro grating was also manufactured (see Figure 5 below) and tested. Polarisation analyses for both TANGO Nitro and TANGO Carbon were performed. The effect on the retrieval was then analysed through end-to-end performance simulators.

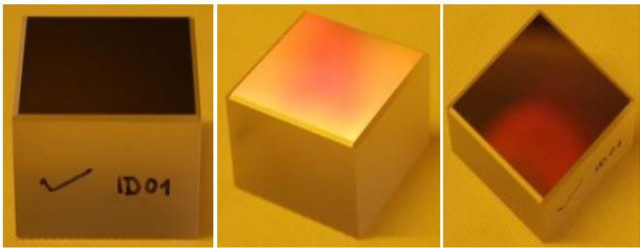

Figure 5. TANGO Nitro master grating (credits: TNO).

For both instruments, straylight and polarisation analyses were performed. TANGO Carbon straylight analyses were performed for a conventional scene (half Tropical Bright, half Tropical Dark transition at nadir). It was shown that $CO_2$ and $CH_4$ retrieval is insensitive to straylight due to the use of the proxy method. Based on the preliminary straylight analysis for TANGO Nitro, the impact on retrieval is expected to be low and can be improved with coating optimisation.

Preliminary tolerance analysis and preliminary plan for both payload alignment and integration were prepared. The alignment philosophy for TANGO instruments requires relatively tight manufacturing tolerances (on the order of ±20 µm) to minimize the duration and cost of the alignment phase. The optics have tolerances on the order of ±20 µm, based on production tolerances of the optical component and housing of ±10 µm and ±15 µm, respectively.

STOP analysis was performed for TANGO Carbon instrument for on-ground integration, ground-to-orbit (GTO) launch and in-orbit operations. It was shown that for on-ground integration, effect of mounting deformation is very low with respect to top-down allocation. For in-orbit operations, preliminary STOP analysis was made taking into account satellite thermal environment and microvibrations. The only micro-vibrations source on-board the spacecraft is reaction wheels. It was shown that microvibrations have minimal impact on the instrument stability. The results of the thermal GTO case analysis were taken into consideration in the alignment procedure to minimise the impact on performance.

### 2.1 DETECTOR CHARACTERISATION and SELECTION

One of the major risk retirement activities was the TANGO Carbon detector characterisation and selection. At the end of the consolidation phase two candidate detectors were identified: one based on Indium Gallium Arsenide (InGaAs) technology, and another one based on Mercury Cadmium Telluride (MCT) technology. During the RRA, SRON characterised and traded-off two InGaAs and one MCT cameras.

Due to lower mass, volume, power consumption, and no cryo-cooler induced micro-vibrations, InGaAs based detectors are strongly preferred. However, significant performance risk was identified in terms of low quantum efficiency (QE) and temperature dependence at 1675 nm wavelength. The alternative was identified to be MCT based detectors.

An extensive characterisation campaign showed that the mentioned risk was fully mitigated. Two cameras based on Cardinal 640 (Semiconductor Devices, Israel) and Snake SW (Lynred, France) showed that the required spectrum can be covered when operating at relatively warm temperatures (see Figure 6). It was also shown that the analogue output of the Snake SW had an advantage in terms of a much lower signal-dependent offset, resulting in Snake SW being the selected detector.

The full testing campaign also included temperature dependence of all major performance parameters, including the dark current, QE, read-out noise, offset. Additionally, TID testing was also performed which showed a significant margin with respect to TANGO expected end-of-life (EoL) mission dose. Impact of displacement damage and random telegraph signal (RTS) from the total non-ionising dose (TNID) was assessed from the available literature on Snake SW detector.

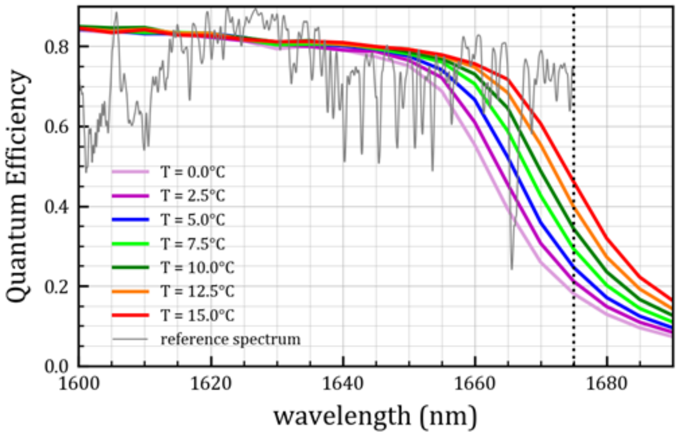


Figure 6. Measured temperature dependence of the Snake SW QE from 1600 nm to 1690 nm. Also provided is an overlay of the TANGO Carbon reference spectrum (grey) (credits: SRON).

## 3 STRUCTURAL-THERMAL MODEL DEVELOPMENT and TESTING

A TANGO Carbon STM was built and tested during the RRA, by ISISPACE and TNO. The STM included platform STM and instrument STM. Platform STM was representative of the baseline FM design, including full primary and secondary structures, both body-mounted and deployable panels and some of the subsystems, which ensured representative mass properties. Instrument STM included representative interfaces to the platform (including the damping struts) and the InGaAs camera.

The instrument STM shown in Figure 7, before being integrated with the platform STM, underwent resonance survey test which results were used to correlate the FEM model. The integrated satellite STM testing campaign included resonance survey, launch loads testing, thermal balance testing and micro-vibration testing. See Figure 8 and Figure 9 below.

Launch loads tests allowed to verify the spacecraft STM compliance with launch vibration and shock loads profiles specified by various launch service providers. After correlating the FEM with the test results, minor design adjustments were identified to ensure spacecraft compliance with the launch profiles.

Thermal balance test allowed to measure the coupling between the equipment and surfaces in the spacecraft STM assembly. The test was performed on the spacecraft assembled inside of a black aluminium enclosure, which was positioned inside the vacuum chamber. The temperatures of the enclosure, spacecraft exterior and interior were controlled in a closed loop. The vacuum chamber shroud and cold plate were cooled to -70 °C and -120 °C, respectively. The thermal model was correlated with the test results. Further improvements to satellite thermal design were suggested to ensure compliant instrument performance.

Micro-vibrations test showed that the effect of micro-vibrations on the performance of the Carbon instrument is low (through STOP analysis).

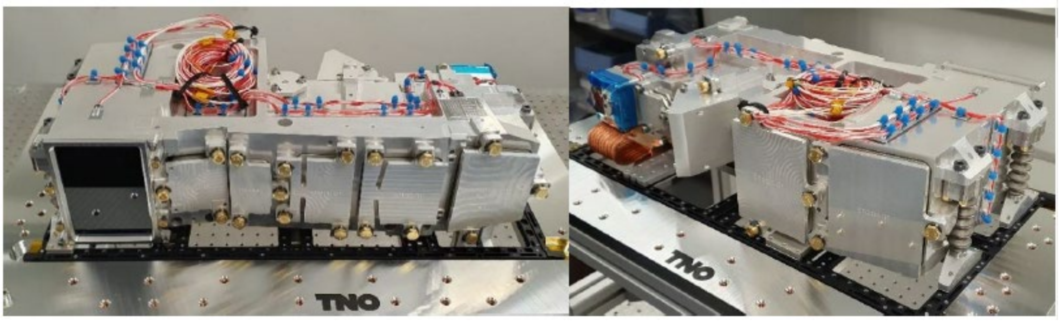


Figure 7. TANGO Carbon instrument STM (credits: TNO).

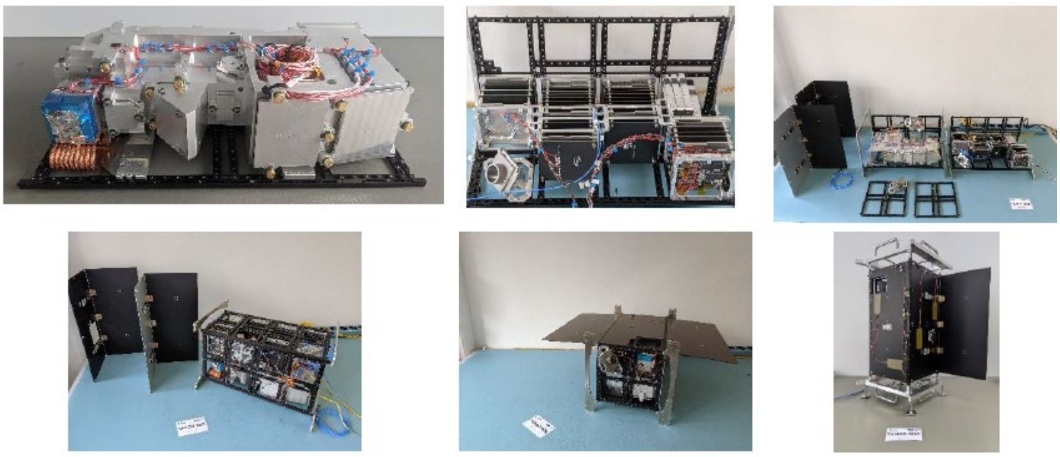

Figure 8. TANGO Carbon STM integration process (credits: ISISPACE).

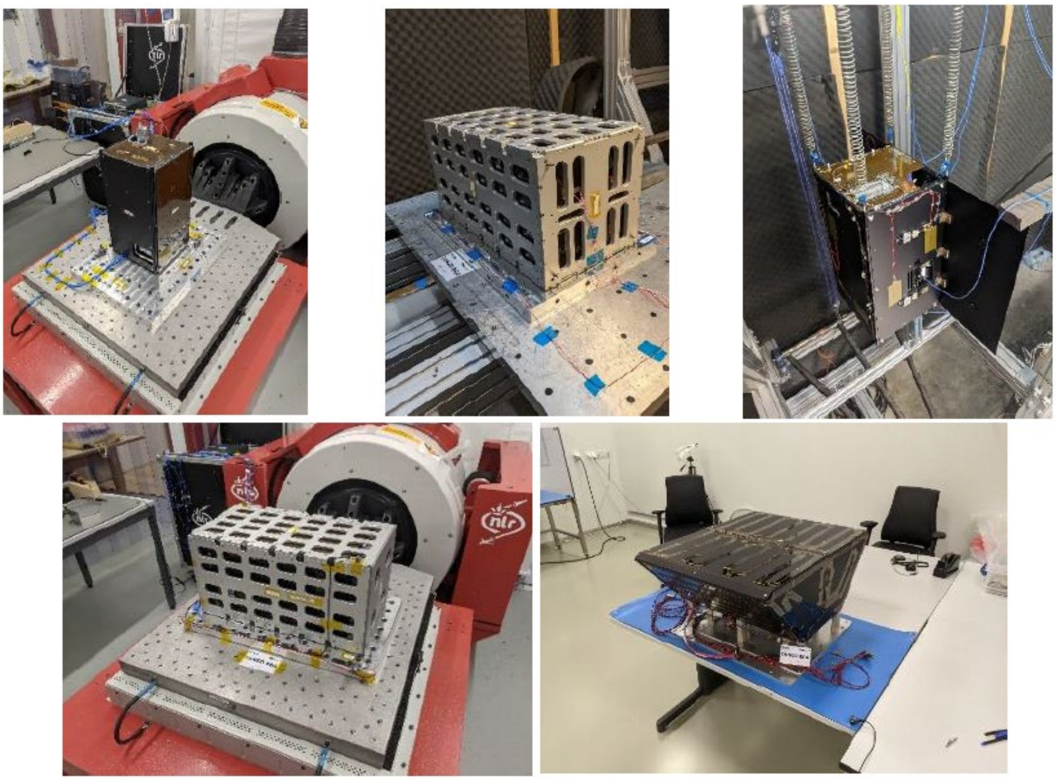

Figure 9. TANGO Carbon STM testing campaign. From top left: resonance survey, launch loads – shock, micro-vibrations. From bottom left: launch loads – vibration, thermal balance (credits: ISISPACE).

## 4 PERFORMANCE SIMULATOR

Two end-to-end (E2E) performance simulators were further developed and used to validated L2 product performance. One simulator was developed by SRON to validate CO2 and CH4 total column accuracy, retrieved by TANGO Carbon. Another simulator was developed by KNMI to validate NO2 total column accuracy, retrieved by TANGO Nitro. The processing chain of SRON is shown in Figure 10. It includes a geometry module (GM), a scene generator module (SGM), an instrument module (IM), a level-1A to level-1B processor, a level-1B to level-2 processor, and a level-2 to level-4 processor. Similar architecture was also used by KNMI.

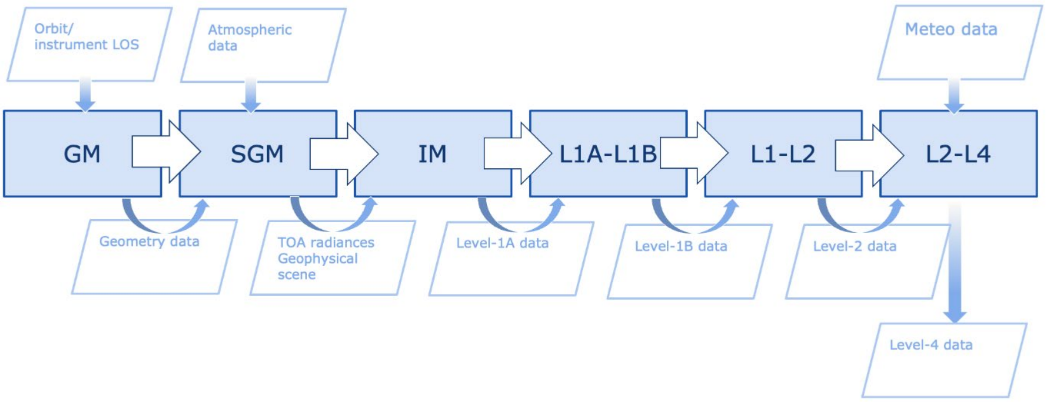


Figure 10. TANGO Carbon E2E performance simulator processing chain (credits: SRON).

Some of the measured and simulated instrument performances that were used within the simulator: instrument spectral response function (ISRF), polarisation sensitivity, straylight, InGaAs detector characterised data. L2 data product precision, as a function of the detector temperature is shown in Figure 11. This figure shows that the proxy precision improves for higher detector temperatures.

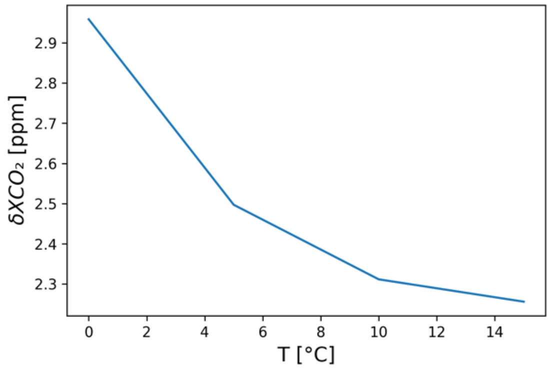


Figure 11. TANGO Carbon E2E simulation of the $XCO_2$ precision as a function of the detector temperature of the Snake SW detector (credits: SRON).

Additionally, InGaAs detector performance degradation due to radiation effects at the end of life was also assessed through the E2E simulator. It was concluded that dedicated dark current monitoring of TANGO Carbon detector during the lifetime of the mission will be required.

Simulation with the TANGO Nitro E2E simulator showed that the L2 product $NO_2$ column accuracy is expected to meet the requirements. The simulator used grating testing results and polarisation sensitivity, spectrometer ISRF and the noise model. Worst case maximum polarisation and solar zenith angle (SZA = 70°) were used for the simulations. One of the next steps identified were combining TANGO Carbon and TANGO Nitro E2E performance simulators.

### 4.1 CLOUD CLEARING ALGORITHM

The proxy method for retrieving $CO_2$ and $CH_4$ products is sensitive to cloud contamination. Therefore, a cloud-clearing step is required. Initially, a machine learning cloud detection algorithm was developed by KNMI for inferring with visible data retrieved by TANGO Nitro. However, as both TANGO Carbon and TANGO Nitro satellites are flying in loose formation (approximately 60 sec apart), the clouds position changes between both measurements. Therefore, a solution of applying cloud algorithm separately to TANGO Carbon and TANGO Nitro was proposed and is further to be assessed in the next phase of the project.

## 5 CONCLUSION

TANGO RRA activity was concluded in Q1 2024 with the following main outcomes:

1. **Instrument technologies maturation**. The optical designs of both TANGO Carbon and TANGO Nitro instruments was further detailed. The detector technology for TANGO Carbon was chosen to be based on InGaAs, which allows to simplify the TANGO Carbon system design (less micro-vibrations, lower mass, volume and power consumption). A TANGO Nitro grating sample was manufactured, and its performance assessed.
2. **Structural-thermal model (STM) de-risking**. The interfaces between the platform and the instrument were de-risked through several STM tests. Thermal and structural models were further improved and design updates for the next TANGO phase suggested.

3. **Payload performance simulations**. TANGO end-to-end performance simulations showed that the challenging needs of the mission can be met. The L2 performance ($CO_2$, $CH_4$ and $NO_2$ total column accuracy) was validated.

After the conclusion of TANGO RRA, the mission has been approved to proceed to implementation stage under the Scout framework.

## ACKNOWLEDGEMENT

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