

International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas



The Tropomi instrument: last steps towards final integration and testing

J. Doornink

J. de Vries

R. Voors

J. Dingjan

et al.



International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 10563, 1056342 · © 2014 ESA and CNES
CCC code: 0277-786X/17/\$18 · doi: 10.1117/12.2304148

THE TROPOMI INSTRUMENT, LAST STEPS TOWARDS FINAL INTEGRATION AND TESTING

J. Doornink¹, J. de Vries¹, R. Voors¹, J. Dingjan¹, B. Ording¹, N. van der Valk², R. Vink², R. Hoogeveen³,
J. Grant⁴, T. Canas⁴, Q. Kleipool⁵, P. Veeffkind⁵.

¹Dutch Space B.V., The Netherlands, ²TNO, The Netherlands, ³SRON, The Netherlands,

⁴SSTL, United Kingdom, ⁵KNMI, The Netherlands.

I. INTRODUCTION

The Tropospheric Monitoring Instrument TROPOMI is ready for system level verification. All sub-units have been integrated and tested and final integration at Dutch Space in Leiden has been completed. The instrument will be subjected to a testing and calibration program and is expected to be ready for delivery to the spacecraft early 2015. Using TROPOMI measurements, scientists will be able to improve and continue the study of the Earth's atmosphere and to monitor air quality, on both global and local scale.

TROPOMI is a passive UV-VIS-NIR-SWIR imaging spectrograph and as such is the next step in a series of successful instruments like SCIAMACHY, GOME and OMI. TROPOMI is the only instrument on the Sentinel 5 Precursor satellite (S5P), indicating also its function as a forerunner for the Sentinel 5 instrument. Compared with its predecessors, TROPOMI will be a major improvement in terms of spatial resolution and data quality.

In previous papers on TROPOMI, emphasis has been on the performance specifications and on some novel technologies applied in TROPOMI [1, 2].

This paper provides a short recapitulation of TROPOMI's main features, presents some test results obtained and provides an overview of the verification steps still to come. Subsystem test results are very promising and we anticipate that TROPOMI will fully meet the user's expectations.

The Sentinel 5 precursor (S5p) space segment comprises Airbus' AS250 platform and TROPOMI as single payload. The S5p is part of the Global Monitoring for Environment and Security (GMES) program which is a joint initiative of the European Community (EC) and the European Space Agency (ESA). The TROPOMI instrument is jointly funded by the Netherlands Space Office (NSO) and ESA and a joint development by Dutch Space and TNO. The science responsibility is covered by KNMI (Royal Netherlands Meteorological Institute) and SRON (Netherlands Institute for Space Research).

Dutch Space is the Instrument Prime for TROPOMI. Dutch Space together with TNO provide the UVN optical bench module, whereas SSTL UK provides the SWIR module. The sub-contractors for the remaining flight hardware are Astrium Germany, RUAG Switzerland, RUAG Sweden, SRON, E2V and Sofradir. KNMI is the Principal Investigator (PI) and SRON is the co-PI for the S5p data products.

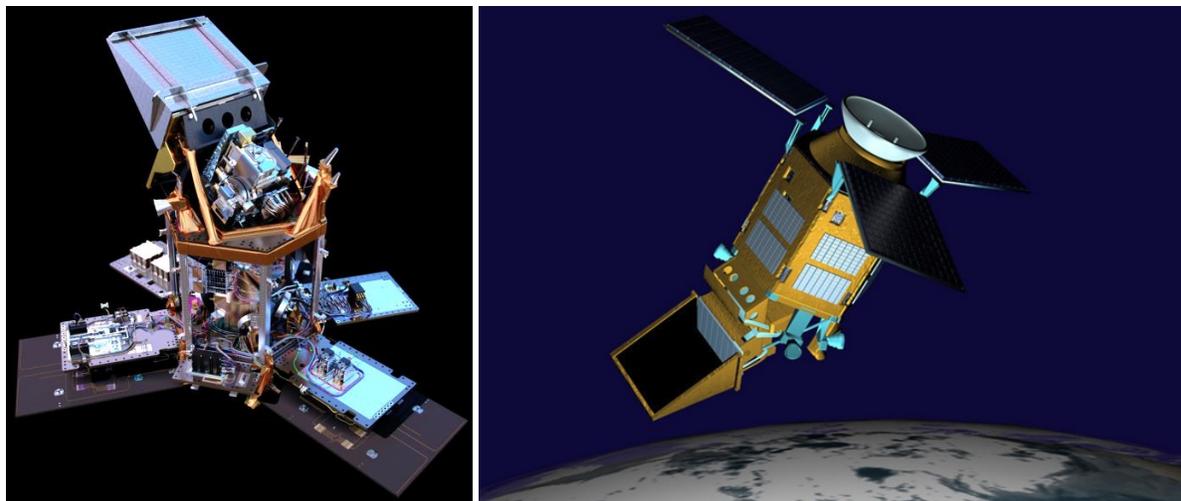


Figure 1. The left picture shows the TROPOMI Spectrometer Equipment and Radiant Cooler mounted on the top floor of the S5p spacecraft. The picture on the right is an artist impression of the S5p spacecraft with the TROPOMI payload in orbit. [Courtesy of Airbus Ltd.]

III. TROPOMI DESIGN FEATURES AND TEST RESULTS

A. Overview

As shown in **Figure 1**, the TROPOMI Spectrometer Equipment and the Radiant Cooler -an advanced passive thermal radiator to cool the instrument at various temperature levels- are mounted on the spacecraft top floor.

Mounted inside the spacecraft is the Instrument Control Unit.

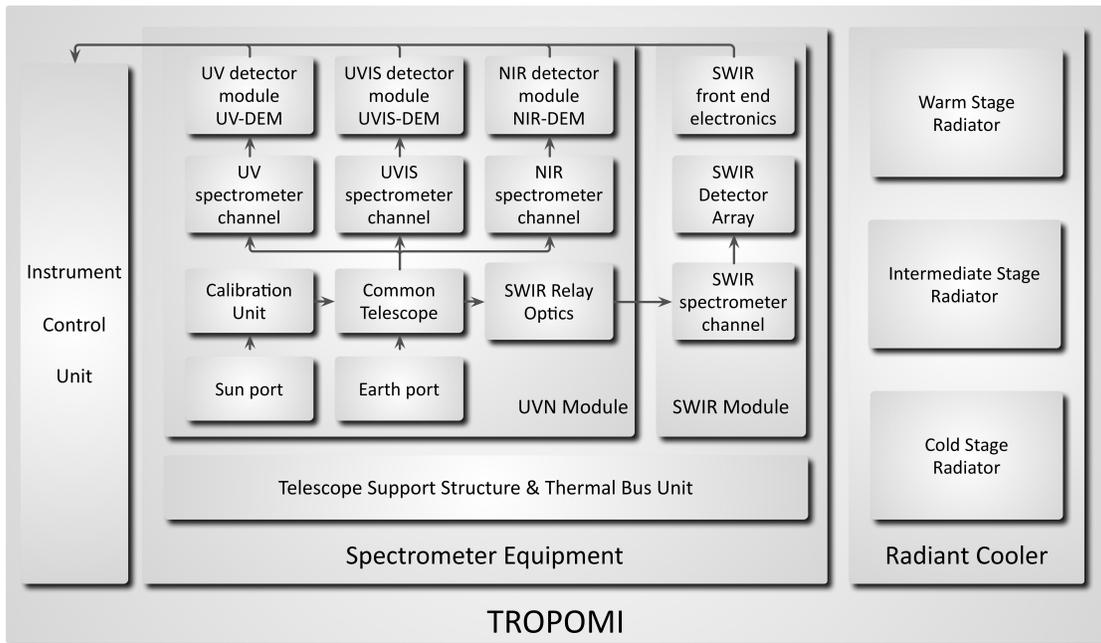


Figure 2. TROPOMI overview.

The following sections focus on design features and test results of the core TROPOMI instrument, the Spectrometer Equipment.

The UVN module consists of the telescope and calibration unit –which are shared by the UVN and the SWIR– and the 3 UVN spectrometer channels (UV, UVIS and NIR), each equipped with individual detector modules. A polarisation scrambler is placed in the optical path to make the measurements insensitive to the polarisation state of the incoming light. The telescope has a very wide field-of-view of 108°. The system will have a spatial resolution of approximately $7 \times 7 \text{ km}^2$ at nadir and covers a swath of 2670 km providing global daily coverage from its sun-synchronous orbit. Nominal observations with this resolution and the obtained signal-to-noise ratios are sufficient for trace gas retrieval even at very low albedos (2 to 5%). This allows daily observations of air quality at sub-city level.

All detectors are optimized for the light that they will detect. The UVIS and NIR detectors have a graded anti-reflective coating, in order to reduce stray light and decrease interference effects in the Silicon. The detectors are cooled to $\sim 210\text{K}$ to reduce the dark current contribution.

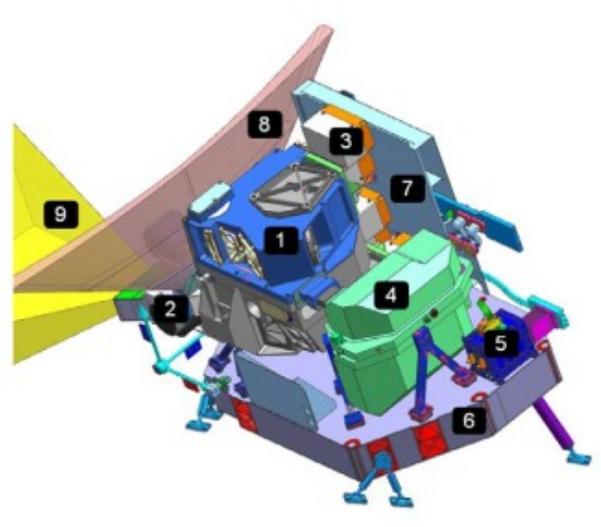


Figure 3. Layout of the TROPOMI Spectrometer Equipment: (1) UVN Module, (2) Calibration Unit, (3) UV, UVIS and NIR DEMs, (4) SWIR Module, SWIR FEE (5), (6) Telescope Support Structure, (7) Thermal Bus Unit, (8) Nadir Field of View, (9) Solar Field of View.

The SWIR module receives light via the telescope and relay optics in the UVN module. The SWIR consist of an optical bench and a detector module with associated front-end electronics. The optical bench is cooled to ~200K to reduce thermal self-emission and the detector is cooled to ~140K to suppress dark current. The SWIR module makes use of an immersed grating [2] which makes it possible to have a compact optical design.

B. UVN Detectors

The UVN detectors for the TROPOMI instrument were designed, built and tested by e2v in the UK. In order to meet the most important performance requirements the photon flux per detector pixel is very high in TROPOMI. This leads to high frame rates and this in turn requires very fast frame transfers in order to minimize the frame transfer smear effect. For this reason it was decided to use metallized electrodes. This enables an order of magnitude faster frame transfer than for standard frame transfer CCDs. The pixel size of $26 \times 26 \mu\text{m}^2$ did not allow a 4-phase pixel in addition to the metallized electrodes, so as a consequence the pixel full well was limited to 700 k electrons.

During the production of the engineering models some issues appeared.

It came to light that the electrical insulating properties of the AR coating were not sufficient for the UV and UVIS detectors to insulate the metal shield to form the storage region from underlying silicon. To overcome this, design improvements have been made.

A further issue arose when the flight models were tested to the full extent. To allow for on-chip binning, the TROPOMI CCDs have a 4 times higher charge handling capacity in the register than in the image pixels. Tests with full register filling showed that it was very difficult to fulfill both the charge transfer efficiency performance as well as the charge handling capacity at the same time. To allow for both, the shape of the originally proposed clock pulses had to be changed significantly, leading to a late modification in the front-end electronics.

C. UVN Detector Modules

After detector level acceptance tests, the detectors were integrated into the Detector Electronics Modules (DEMs), by RUAG Space in Switzerland.

The front-end electronics of the UVN-DEM makes use of a 14-bit analogue frontend (AFE), which performs both CDS and the Analogue to Digital conversion. The front-end electronics is located on a PCB very close to the detector to minimise interference effects on the analogue signal chain. The detector is mounted on a hexapod frame in order to provide a rigid mechanical interface with the housing of the focal plane assembly and to thermally isolate it from the housing. This is necessary because the detectors will be operated around 200 K whereas the electronics and the housing will be at ambient temperature.

Two outputs per detector are used both at 5 MHz readout frequency. To optimize the performance of the signal chain, each output is equipped with a dedicated amplification, to match the radiance levels of the incoming spectrum. In addition, gain optimisation is possible by switching the detector output responsivity

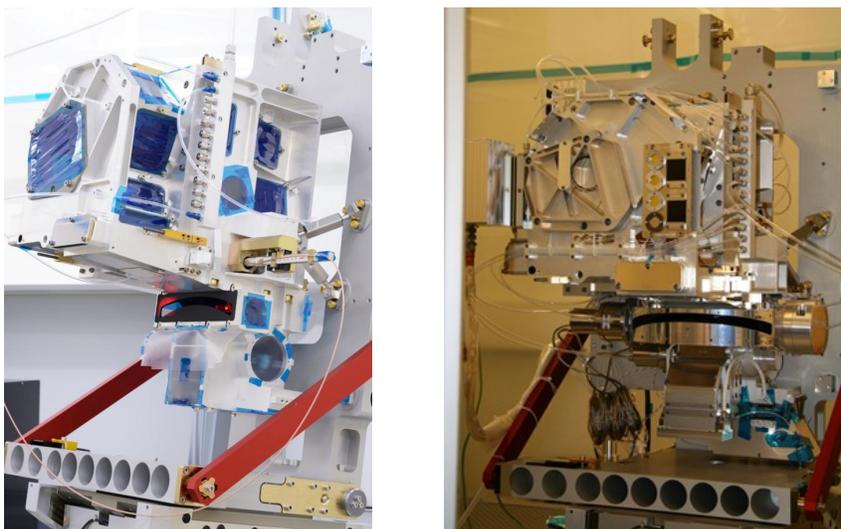


Figure 4. Photographs of the UVN module. The left picture is an early picture in which only the telescope mirrors are integrated. In view of effective purging for contamination control, all vacant mounting holes are covered by blue foil. The right picture shows a later status in which almost all components are integrated and all purge lines are installed on the purging manifold. The horizontal curved slit is the nadir opening. The UV-DEM is visible on the right side of the UVN Module.

(by roughly a factor of 2) as well as in the AFE (with gains between 0.65 and 8.2). This system allows for a lot of flexibility in the operations of the instrument.

Acceptance testing of the DEMs was performed at the end of 2013, after which they were integrated onto the UVN Module in early 2014.

D. UVN Module

All UVN module components have been subjected to an extensive breadboard program including vibration and thermal testing. In this breadboard program the design of the mounts of transmission optics and the gratings has been qualified. Also, each and every flight mounted optical component has been subjected to a proof test before integration in the UVN Module structure, which houses the three channels in a very compact envelope.

Integration and alignment of the calibration unit, the common telescope the UVIS, NIR and UV spectrometers and the SWIR relay part has been completed early May 2014 (see **Figure 4**).

After integration of the telescope and each of the spectrometers, their performance is rigorously checked. The results for the TROPOMI telescope are illustrated in **Figure 5**. The results show an excellent imaging quality. The TROPOMI 7 km ground resolution corresponds to 0.5° at instrument level, taking into account the 820 km orbit height. The spot sizes achieved with this telescope are only a small fraction of this.

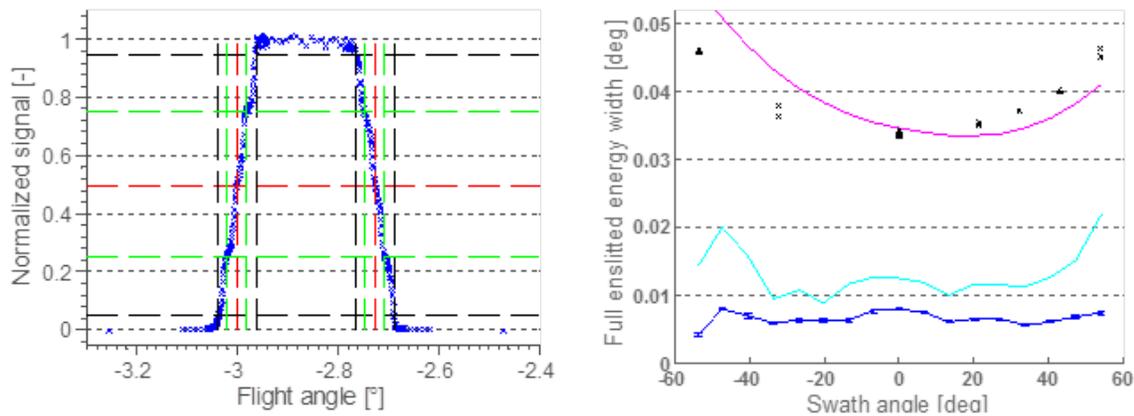


Figure 5. Telescope spot measurement. The left picture shows a typical result of the telescope spot size measurement in which a star simulator is scanned perpendicular to the instrument field-of-view. The steps due to the scrambler diamond are clearly resolved. The right picture shows excellent spot sizes, expressed as 50% ensilted energy width, for various field points. For comparison, the solid lines show theoretical predictions for the nominal system (dark blue), including tolerances (cyan) and including tolerances and scrambler diamond (purple).

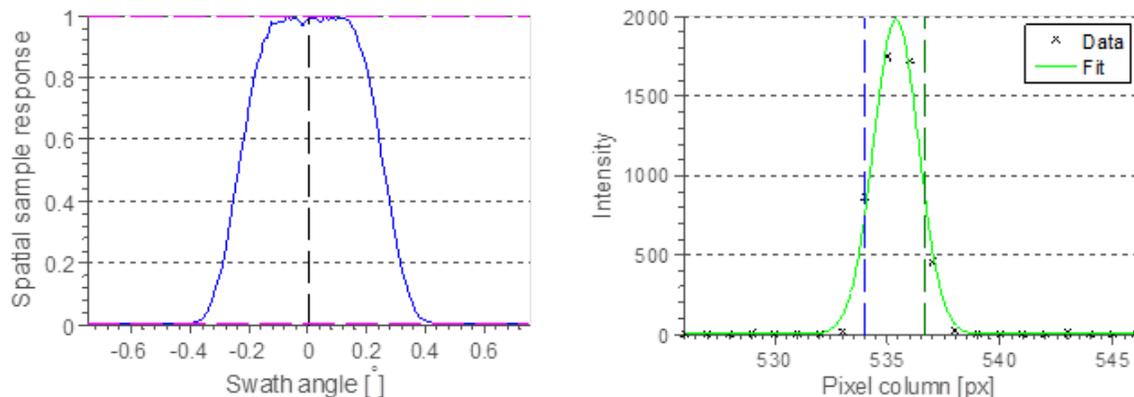


Figure 6. Spatial and spectral resolution. Left: a typical spatial spot size measurement, in which the output of a single (binned) pixel is recorded while a star simulator is scanned across the pixel in across-track direction. Right: a typical spectral resolution measurement in which the instrument is illuminated with a spectral line source. The crosses represent measurements at different pixels; the green line is a Gaussian fit through the data, from which the spectral resolution can be determined.

For the UVIS, NIR and UV spectrometers the spatial and spectral resolution has also been confirmed. The measurement of spectrometer (across-track) image quality is illustrated in Figure 6 left. The response of a binned pixel to a scanning star simulator is recorded, where steep flanks demonstrate good imaging quality.

The widths of the spectral response functions (example in Figure 6 right) are within the boundaries of minimum spatial sampling and maximum spatial resolution. This is especially good news for the UVIS spectrometer, where the exceptionally large spectral range (310-495 nm) combined with the relatively small detector, results in only 10% margin between the minimum and maximum widths of the spectral response function.

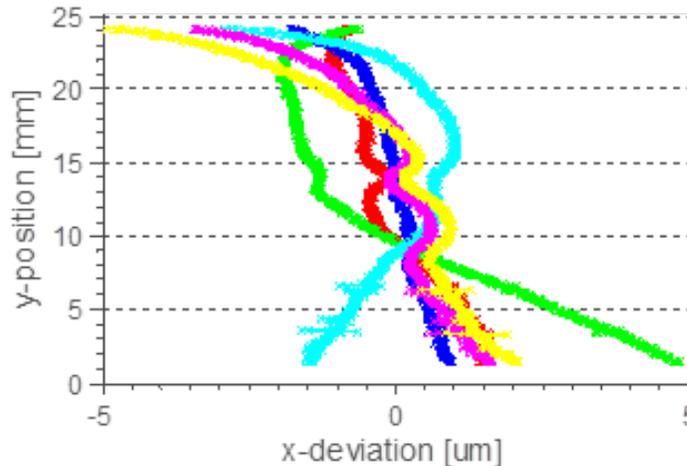


Figure 7. Final measurement of the UVIS intra-channel across-track co-registration. The vertical axis shows the spectral (y) location on the detector; the horizontal axis show the mis-registration in microns on detector level. Different lines represent different swath angles.

The intra-band co-registration is measured with a white-light star simulator. Ideally, this should give perfectly straight lines on the detector aligned with the pixel columns. Figure 7 shows the results for the UVIS spectrometer with peak-to-peak deviations below 10 μm , which compares nicely with the 104 μm size of a binned spatial pixel. The NIR results (not shown) are even better.

E. UVN Signal-to-noise status

Having available measured detector performances and optics element throughputs, it is useful to present signal-to-noise estimates derived from these measured performances. Multiplying the measured coating data on all individual optical elements and using the measured detector QE, full wells and readout noise produce the estimates. Figure 8 shows the results for the S5p reference spectra representing quite dark scenes (albedo 2%).

Concluding, the UVN module performance as demonstrated up to now is excellent. The UVN module has been integrated on the Telescope Support Structure and aligned with the SWIR module. The next steps are the verification of alignment stability and radiometric performance in vacuum during the pre-environmental tests.

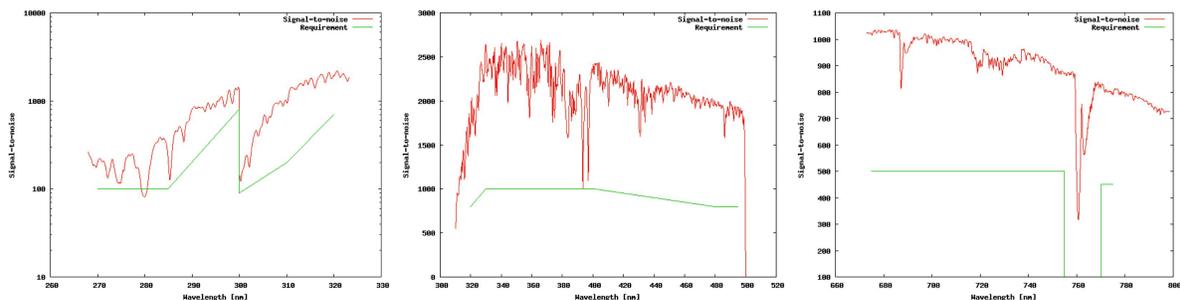


Figure 8. Calculated S/N values (red curves) using measured unit performances and for a 2 % albedo scene (top graph UV, center UVIS and bottom the NIR band); the green lines show the project S/N requirements, making clear that TROPOMI performs very well.

F. SWIR Detector and front end electronics

The TROPOMI SWIR spectrum is projected onto a Sofradir-developed 2D detector array consisting of 1000 spectral pixels and 256 spatial pixels on a 30 μm pitch, the Saturn geometry.

The SWIR detector is mounted in a package with an anti-reflection coated silicon window. The detector package is mounted onto a molybdenum base plate; attached to an aluminum cold finger providing the connection to the cold-stage radiator, see Figure 9. Operational temperature of the SWIR detector is 140 K.

The cold detector is connected to the 200 K SWIR spectrometer by a thin-walled titanium double cone. This construction is very stable, closed for Electro-Magnetic Interference (EMI) and provides thermal insulation. An anti-reflection coated silicon window just before the SWIR detector prevents any water vapour from freezing onto the cold detector window. The small volume around the detector is vented through the cold finger and via a flexible tube to the cold stage of the radiant cooler, acting as a cold trap. The measures to prevent water from reaching the detector are based on lessons learned from the ENVISAT/SCIAMACHY SWIR channels.

The SWIR detector is powered and commanded by front end electronics (FEE) mounted on the Telescope Support Structure and operates at room temperature. The SWIR detector is read with a pixel speed of 800 kHz, leading to a frame-read time of 82 ms, and a maximum frame rate of 12 Hz. The FEE controls the detector temperature by reading the two internal T-sensors of the Saturn detector and a PID algorithm in the FPGA. Thin-film heaters are mounted at the back of the molybdenum plate. Typical detector temperature stability obtained is 6 mK rms.

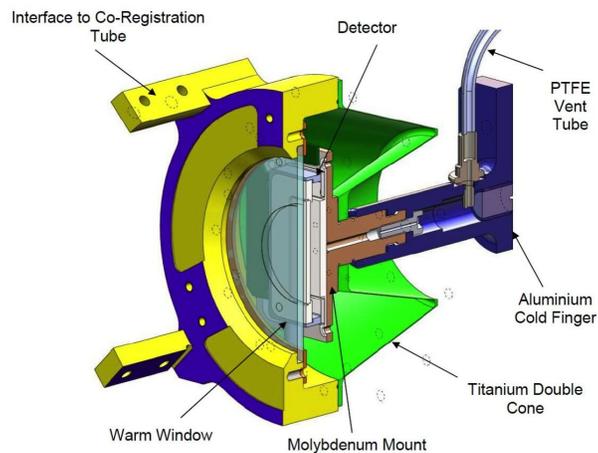


Figure 9. Schematic of the SWIR detector module

The combination of the TROPOMI SWIR detector and its FEE has been thoroughly characterized by SRON, see [3]. Only the memory between two consecutive readings is with 1.6 - 1.9 % out of spec, leading to a data correction. Where this correction is not complete an effective smear of information from one ground pixel to the next has to be accepted. The detector performance on sensitivity, dark current, noise, and their uniformities are better than specified, as well as the linearity and the number of dead pixels. Overall, the performance of the SWIR detector and its FEE is considered very good for the TROPOMI application.

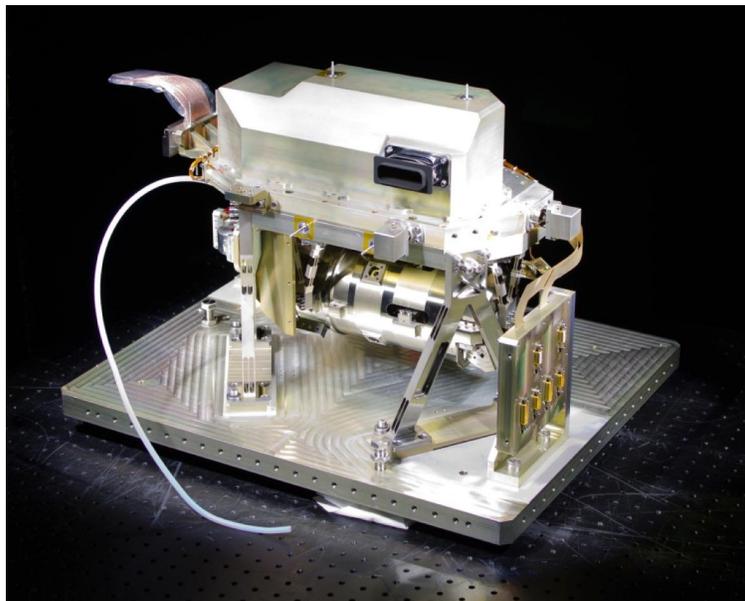


Figure 10. TROPOMI SWIR Spectrometer Module

G. SWIR Module

The Short Wave Infra-Red (SWIR) Module on TROPOMI, designed and developed by SSTL, is a push broom grating spectrometer operating between 2305 nm and 2385 nm. The SWIR Module will be used to measure the concentration of methane and carbon monoxide in the Earth’s atmosphere.

The optical design consists of a telescope, slit, collimator, immersed grating, anamorphic prism and an imaging lens. The SWIR telescope forms an image of ground on the SWIR Spectrometer slit. The slit acts as a spatial filter selecting a strip of ground as an input to the rest of the spectrometer. A collimator takes light from the slit and creates collimated beams as an input to the immersed grating. The immersed grating disperses the collimated beams in the along track direction and the anamorphic prism and imaging lens form a dispersed image of the slit on the detector. A band pass filter is manufactured as part of the slit prism and restricts light that can reach the detector from outside the operational waveband.

The SWIR immersed grating is supplied by SRON and Sofradir supplies the SWIR detector. The assembled SWIR module is shown in Figure 10. Figure 11 and Figure 12 show performance measurement results of this module.

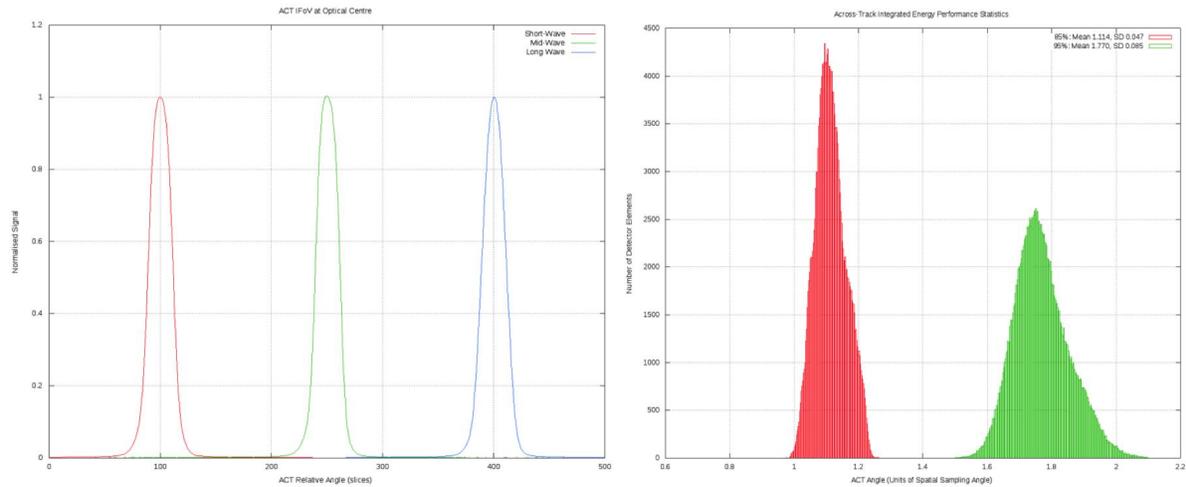


Figure 11. The integrated energy performance of the SWIR Module in the across-track direction. The measurements demonstrate that the SWIR module achieves 85% of the integrated energy within 1.25 spatial sampling distances and 95% of the integrated energy within 2.05 spatial sampling distances.

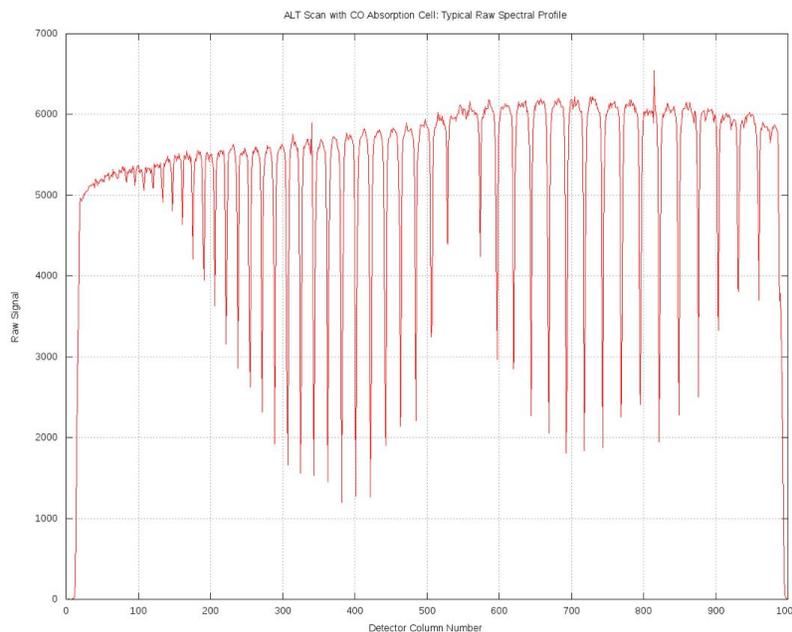


Figure 12. Example spectral profile captured by the SWIR module when illuminated with a carbon monoxide gas cell. Based upon measurements made with this cell the spectral resolution of the SWIR module was found to be better than 0.225 nm across the wavelength band.

IV. TROPOMI VERIFICATION AND CALIBRATION PROGRAM

The TROPOMI instrument is now ready for the upcoming instrument level testing and calibration program. At the point of writing this, the preparations are in full swing. The fit-check between the Spectrometer Equipment and the Radiant Cooler has just been passed successfully and the instrument is being made ready for the pre-environmental testing where the instrument performance in vacuum and at representative temperature will be verified. After environmental testing the performance is verified again and the calibration campaign is carried out. The radiant cooler is tested separately and meets the instrument again at spacecraft integration.

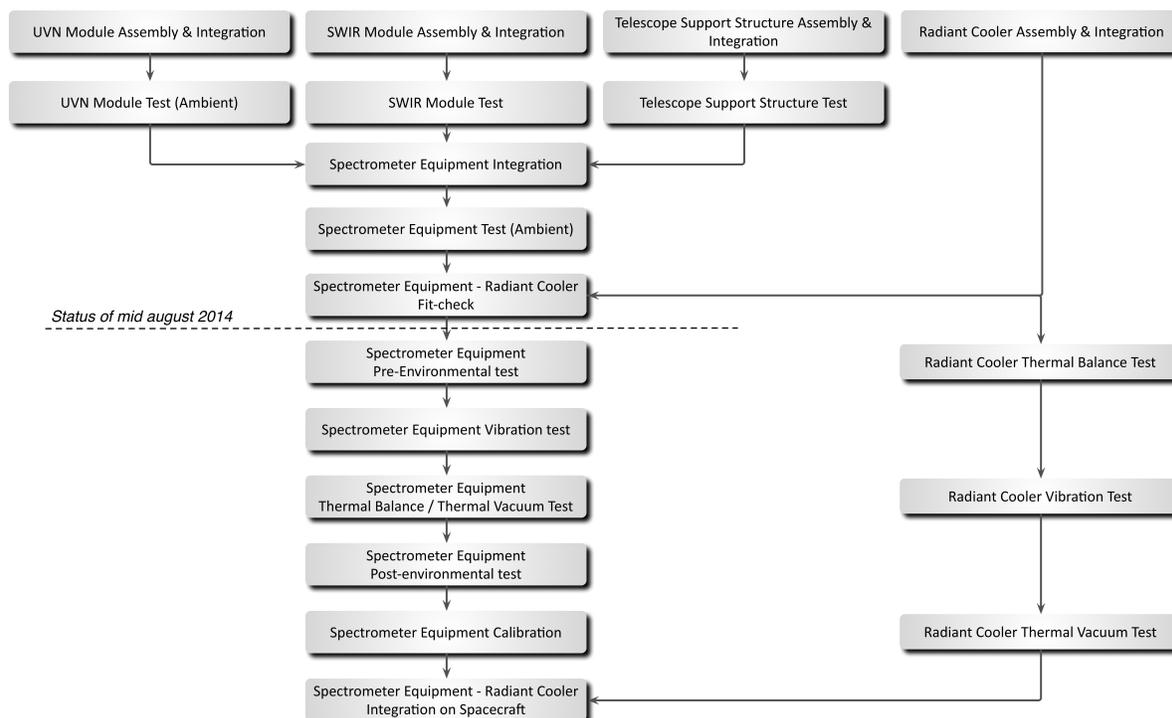


Figure 13. Overview of TROPOMI assembly, integration, test and calibration program

V. CONCLUSION

The testing program of the TROPOMI instrument is well on its way. Module level test results so far look very promising. Although being a pre-cursor mission which is assembled, integrated and tested on a very challenging schedule, the TROPOMI test results presented here show that the instrument is well on its way to meet the significant performance improvements over its predecessors.

REFERENCES

- [1] Robert Voors, Johan de Vries et al., "TROPOMI, the Sentinel 5 Precursor instrument for air quality and climate observations: status of the current design" in Proceedings of ICSO 2012.
- [2] Aaldert van Amerongen, Hélène Krol, Catherine Grèzes-Besset, Tonny Coppens, Ianjit Bhatti, Dan Lobb, Bram Hardenbol, Ruud Hoogeveen, "State of the art in silicon immersed gratings for space" in Proceedings ICSO 2012, paper FP_ICSO-070.
- [3] Hoogeveen R.W.M., Voors R., Robbins M.S., Tol P.J.J., Ivanov T.I., Characterization results of the TROPOMI Short Wave InfraRed Detector, Sensors, Systems, and Next-Generation Satellites XVII, Proc. of SPIE Vol. 8889, 888913..