Breadboarding activities of the TROPOMI-SWIR module

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ABSTRACT

The TROPOMI instrument concept is part of the TRAQ mission proposal to ESA in response to the Call for Ideas in 2005. TRAQ (TRopospheric composition and Air Quality) has been accepted for a further pre-phase A study for the next Earth Explorer core Mission. A very similar instrument has been proposed for the CAMEO platform to the US National Research Council decadal study, which has also been accepted for further study.
TROPOMI is a nadir-viewing grating-based imaging spectrometer using the Dutch OMI and SCIAMACHY heritage. It includes an UV-VIS-NIR module that consists of three UV-VIS channels continuously covering the 270-490 nm range to determine O_3, NO_2, HCHO, SO_2, aerosols and a NIR-channel covering 710-775 nm for cloud detection and information on the aerosol height distribution using the oxygen A band. TROPOMI also includes a SWIR module covering 2305-2385 nm that mainly focuses on determination of CO and CH_4 total columns. All species are measured with sensitivity down to the Earth's surface, thus addressing issues of anthropogenic emissions and their impact on air quality and climate. In the TRAQ mission, unique diurnal time sampling with up to 5 daytime observations over mid-latitude regions (Europe, North-America, China) is foreseen by using a non-sun-synchronous, medium-inclination drifting orbit and a 2600 km wide observational swath.
Several more general aspects related to the TROPOMI instrument are discussed in a separate paper in this conference. This paper focuses on the development of the SWIR module. A breadboard model (BBM) has been designed and constructed which is as much as possible functionally flight representative. Critical technologies to be demonstrated with the BBM are the SWIR HgCdTe-based 2D focal plane array, the on-board SWIR calibration LED, and in particular, the SRON/TNO developed silicon-based immersed grating that allows a hugely reduced instrument volume. In the presentation the results of a performance analysis of the TROPOMI-SWIR channel will be discussed, as well as results of the detector characterization program on a representative off-the-shelf FPA, and details of the photolithographic production of the immersed grating.

Keywords: Optical Instrumentation, Remote Sensing, Space Technology, Troposphere, short-wave infrared, immersed grating, methane, carbon monoxide.

1.   INTRODUCTION

The Netherlands have a strong heritage in the design, building, calibrating and data analysis of Earth atmosphere observing instruments, such as the GOME instrument on ESA's ERS-2 satellite (launched in 1995), SCIAMACHY[1] on ESA's ENVISAT (launched in 2002), OMI[2] on NASA's EOS-Aura satellite (launched in 2004), and GOME-2 on EUMETSAT's MetOp (launched in 2006).

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The Dutch teams involved in the previous instruments, and represented in the author list, and their international partners have now defined the next step in the line of instruments: The TROPOMI instrument (Troposheric Ozone Monitoring Instrument) combines all good things of the previous instruments and improves on most specifications. The TROPOMI instrument concept has been proposed as one of the instruments on the TRAQ mission in the framework of ESA's Earth Explorer Core Missions. TRAQ is selected by ESA – together with five other mission proposals - for a pre-phase A study. A subset of these six preselected mission candidates will be selected for phase A. The mission finally selected for implementation will be launched around 2015. The CAMEO proposal to the NSF for the US decadal study is recommended to NASA as a future mission in the 2016-2020 time frame. In addition, the TROPOMI concept fits the recommendation of ESA's CAPACITY study to realize a LEO mission with a UV-VIS-NIR-SWIR nadir viewing spectrometer (GMES/Sentinel 5) [3].

TROPOMI on TRAQ consists of a nadir viewing grating-based spectrometer measuring the spectrum in three UV-VIS channels (270-490 nm), a NIR channel (710-775 nm), and a SWIR channel (2305-2385 nm). The instrument will measure both the Earth radiance and solar irradiance spectra, in combination yielding the reflectance spectrum that contains the information for retrieval of atmospheric trace gases. A major improvement with respect to the SCIAMACHY and OMI capabilities, is the reduced ground pixel size. This not only improves the ability to locate sources and sinks of certain gases, but also dramatically increases the number of cloud-free observations. Due to improved optics and better detectors, also the signal-to-noise performance will improve. The instrument will measure the main tropospheric pollutants (O_3, NO_2, CO, CH_2O and SO_2) and two major climate gases (tropospheric O_3 and CH_4). In addition, it will measure important parameters of aerosols (aerosol optical thickness, single scattering albedo, aerosol absorption index), which play a key role in tropospheric pollution as well as in climate change. Near-global daily coverage and unique diurnal time sampling with up to 5 daytime observations over mid-latitude regions (Europe, North-America, China) can be realized by using a non-sun-synchronous, medium-inclination drifting orbit.

In summary, the main research objectives of the TROPOMI instrument are:

- To contribute to a better quantification and attribution of the sources and sinks of trace gases, including major greenhouse gases, short-lived precursor gases and aerosols on a global scale, and

- To contribute to a better understanding of the atmospheric transport, chemistry and radiation processes that drive the interactions between tropospheric composition, air quality and climate

The main instrument requirements for the TROPOMI instrument have been derived from requirements of the level 2 products and have been reported in earlier SPIE presentations for the UV-vis-NIR part[4] as well as for the SWIR part[5]. This paper discusses the progress made in the detailed design of the TROPOMI-SWIR channel as well as breadboarding activities for the SWIR channel. Progress made on the development of the UV-vis-NIR channels will be reported in a separate contribution to this conference[6].

The paper is organized as follows: first, the main science objectives of the TROPOMI-SWIR channel are discussed in section 2. Section 3 gives details of the instrument design and the most critical parts. In section 4 the breadboard model will be discussed. Section 5 will discuss the production of immersed gratings. Section 6 gives the conclusions and future plans.

2. THE IMPORTANCE OF CO AND METHANE MEASUREMENTS

The TROPOMI-SWIR channel is meant to continue and improve on the unique SCIAMACHY data record of CO and CH_4. So far, there is no other space-based mission that measures CO or CH_4 in the SWIR spectral window. Measuring in the SWIR has the great advantage that, in the absence of clouds, the gases are measured down to the Earth's surface where the main sources of these gases are located.

Methane is the second most important anthropogenic greenhouse gas. Since the industrialization the methane concentration in the atmosphere has more than doubled. The methane concentration shows considerable interannual variations due to climatic effects, and a clear decrease of the growth has been observed in the last two decades. Although the sink of methane, oxidation by OH, is relatively well understood, its sources remain a huge challenge. Both anthropogenic and natural sources are important for atmospheric methane levels. The actual quantification and spatial distribution of the methane sources and their reaction to climate changes are not well known. For this, space-based measurements are extremely important as these cover all relevant areas on the globe contrary to the surface network. Only recently, the SCIAMACHY SWIR channel has identified the tropical forests as a significant source of methane[7].

Later, this was confirmed by lab experiments showing that living plants are able to produce methane [8]. The challenge of satellite observations is to make accurate and precise CH_4 measurements from space. SCIAMACHY has shown this is feasible [9], TROPOMI-SWIR should improve on this, both in quality and in quantity of the measurements..

Carbon monoxide (CO) is an important trace gas in tropospheric photochemical processes. CO is removed from the troposphere mainly by reaction with OH which is the major cleansing agent of the troposphere. The reaction between CO and OH controls the tropospheric OH amount and thus for example the main sink for methane. In that sense, CO is considered an indirect greenhouse gas. In addition, CO can also lead to the production of tropospheric ozone which is a greenhouse gas and an air pollutant. Nowadays more than half of CO emissions are man-made and the result of mainly biomass burning and fossil fuel use. Although it is well established what the sources of tropospheric CO are, the absolute magnitude of individual sources, their seasonality as well as the interannual variation (in case of biomass burning) are quite uncertain. In addition, CO is a rather stable gas and as such intercontinental long range transport of CO pollution is often observed [10]. So measuring CO on a global scale from space is of great importance for both climate change and air pollution perspective.

3. BASIC INSTRUMENT REQUIREMENTS FOR TROPOMI-SWIR

The basic requirements for the TROPOMI SWIR channel have been derived in ref. 5. In the TROPOMI-SWIR spectral range the spectrum is dominated by absorption lines of CH_4 and H_2O, and contains rather weak CO absorption lines. Back-scattered solar light in the SWIR spectral range reaches down to the Earth's surface (provided a cloud-free scene), thus also probing the lowest parts of the troposphere.

Basis of the instrument requirements is the scientific requirement to measure a moderate CO column of 10^{18} molecules/cm^2 with a better than 25% accuracy, even under minimal illumination conditions, set by a 70 degrees solar zenith angle and a 5 % surface albedo. The scientific requirement on methane is to derive the total column with an accuracy of better than 2%. The desired ground pixel size of TROPOMI has been chosen to be 10 x 10 km^2. This is a compromise between the desire to have as small as possible ground pixels for more accurate determination of sources and sinks, and more cloud-free observation on the one hand, and signal to noise ratio and instrument size on the other hand. The selected ground pixel size is about a factor of 35 smaller than the present pixel size of SCIAMACHY, and a factor 3 smaller than OMI.

Based on these top level requirements, the main TROPOMI-SWIR instruments requirements have been derived, and are given in Table 1.

With the derived design, the performance in terms of noise-limited precision in the retrieval of CO and methane columns can be calculated for the minimum scenario, as well as for other illumination scenes (more favorable illumination angles from the sun and higher surface albedo). The results are given in Table 2.

Table 1: Main instrument requirements for the TROPOMI-SWIR channel.

Parameter	TROPOMI
Viewing Geometry	
Platform height	720 km
Swath	2600 km
Across track spatial sampling	8.8 km
Along track spatial resolution	9.4 km
Spectrometer parameters	
Effective telescope area	3.5 mm^2
Spectral range	2305-2385 nm
Full performance range	2314-2375 nm
Spectral resolution	0.25 nm
Spectral sampling	0.125 nm
Optical bench temperature	220 K
Detector parameters	
Quantum efficiency	80 %
Detector temperature	165 K
Typical integration time	1.5 s

Table 2: Achievable S/N for the minimum, nominal and maximum scene for the set of TROPOMI-SWIR channel instrument parameters and corresponding precisions on total columns of CO and CH₄.

Atmospheric scene	S/N	CO precision (10^{18} molecules/cm^2)	CH$_4$ precision (%)
Minimum: SZA =70 dg, SA 0.05	95	0.19	0.50
Nominal: SZA =50 dg, SA 0.20	395	0.06	0.12
Maximum: SZA =10 dg, SA 0.65	1005	0.03	0.05

SZA = Solar Zenith Angle; SA = Surface Albedo.

The TROPOMI instrument design is based on the existing OMI design, and involves push-broom imaging using 2D detector technology[2]. With this technique the complete swath of 2600 km is imaged along one direction of a 2D focal plane array (FPA), while the spectral information is projected along the other coordinate. The telescope is of a wide field reflective telecentric configuration, and is basically a scaled version of the present OMI telescope. The field of view is 114° across flight and about 1.0° in the flight direction. Folding mirrors are used to minimize the instrument size. It is foreseen to include in the telescope design a polarization scrambler, as was applied in OMI. In the SWIR channel, the wavelength range is rather limited, simplifying the scrambler design.

The spectrometer comprises an entrance slit, folding mirrors, a collimator mirror, an immersed grating for dispersion, germanium imaging optics and a 2D FPA. For the flight model instrument the design is still being optimized. Design drivers are signal to noise value, image quality and mass. The most critical elements of the TROPOMI-SWIR optical design are the immersed grating, the 2D SWIR detector array, the polarization scrambler and the SWIR LED on-board calibration source. These elements are currently under study in a breadboard program.
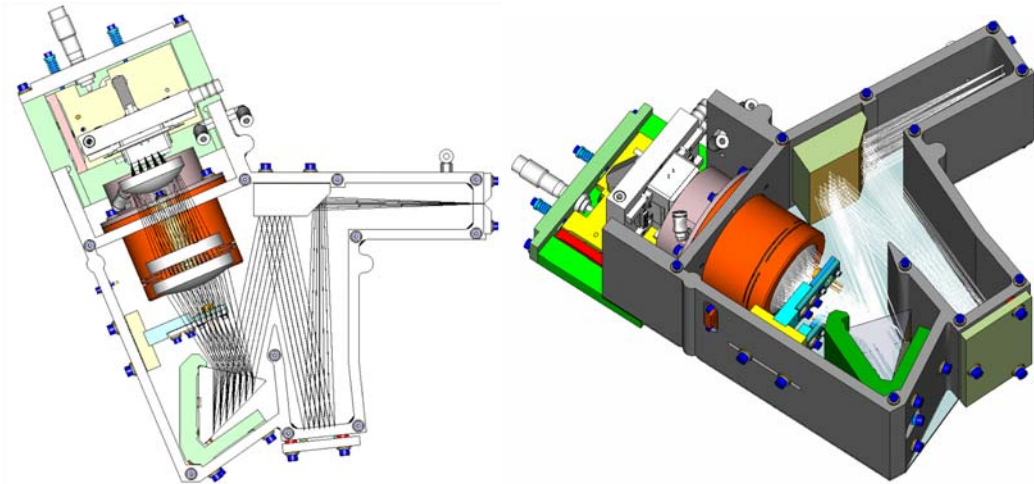
4.   THE TROPOMI-SWIR BREADBOARD PROGRAM

To study the most critical parts of TROPOMI-SWIR, a breadboard program has been initialized. In this program, the optical design of the spectrometer (without the telescope) has been implemented, without taking into account the mass design-driver and other restrictions that are linked to space applications. This greatly speeds up the design and production. The optical layout and mechanical design can be seen in Figure 1. The entrance slit of the spectrometer is located at the right. The light is subsequently folded and directed to the collimator mirror at the lower right. The collimated beam is folded again to the immersed grating. Details of the immersed grating are explained in the next section. The dispersed beam is imaged by a triplet of germanium lenses (orange tube in Figure 1) on the detector array. For on-board calibration purposes two 2.3 μm light emitting diodes (LED23 of the Independent Business and Scientific Group in St Petersburg[10]) are mounted just outside the optical beam between the grating and the camera lenses.

Detection of the spatial and spectral information is performed using state-of-the-art 2D hybrid FPAs employing HgCdTe as the photo-active material bonded to a CMOS read-out IC (ROIC). For the flight model, several vendors of both the US and Europe are under consideration. For the breadboard model (BBM) the Sofradir 2.5 micron TE-cooled MARS detector has been selected[11]. This detector in mounted to have 256 pixels in the spatial direction and 320 pixels in the spectral direction. The maximum sensitivity of this detector material is at 2400 nm, while its TE cooler is able to operate the detector at a minimum of 175 K. The detector readout noise is about 250 electrons.

In the breadboard model, the number of detector pixels is smaller than required for the flight model, both in the spectral and spatial dimensions. Especially in the spectral dimension this is undesired. Therefore, in the BBM the detector is mounted on a platform that can be translated such that the complete required spectral range can be sampled.

The goal of the TROPOMI-SWIR BBM is to demonstrate its functionality and performance by the detection of CO and methane absorption lines in the 2.3 micron range using a gas cell. In a later stage atmospheric measurements will be pursued as well. The results obtained with the BBM will be used to verify the theoretical analysis of the TROPOMI-SWIR module performance.

Figure 1: Design of the TROPOMI-SWIR breadboard model (drawings courtesy of MECON BV).
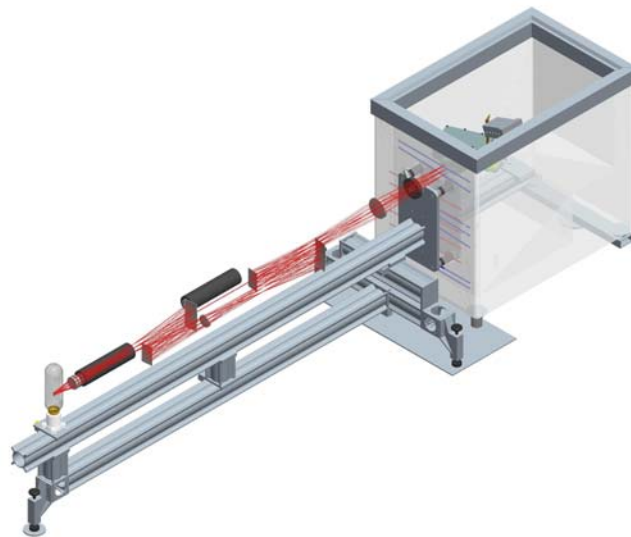
Figure 2: Drawing of the external illumination unit of the TROPOMI-SWIR BBM. A calibrated striplamp is placed on the far left. A gas cell or a polarizer can be placed in the beam directly after the first lens. A second gas cel, can be placed halfway the illumination unit. The BBM is placed inside the commercial freezer at the far right.

The measurement setup to be used is schematically indicated in Figure 2. The BBM is mounted inside a commercial freezer that cools the instrument down to -30 ºC, thus reducing the thermal-background radiation. The freezer is purged with dry nitrogen to avoid ice condensation. A spectral low-pass filter applied on the germanium lens in front of the detector further reduces the background to an acceptable level. A calibrated external striplamp is used to illuminate the slit of the breadboard model. It is possible to place one or two gas cells or a polarizer in the optical path. The illumination unit allows to illuminate the complete swath of the instrument.

At present, the detector is undergoing a test program, with emphasis on detector dark current, noise, non-linearity and pixel-response non-uniformity. Most of these features are characterized as a function of detector temperature and bias voltage. First results will be presented at the conference.

5. IMMERSED GRATING DEVELOPMENTS

The spectral resolution of the TROPOMI-SWIR channel is fairly high, see Table 1. Application of conventional gratings, as applied in SCIAMACHY, would lead to a relatively large and thus heavy instrument. Too heavy for the satellite platform selected for TRAQ. Therefore, the application of immersed gratings is mandatory to reduce the volume and mass. The difference between conventional and immersed echelle gratings is sketched in Figure 3.

In an immersed grating the light first enters a medium with an index of refraction n, which effectively reduces the wavelength of the light by a factor n. After dispersion by the grating surface, the light exits the immersion medium and acquires an extra dispersion due to refraction. Effectively, an immersed grating delivers a factor n more diffraction for the same geometry. This implies that the grating can be made a factor of n smaller while obtaining the same dispersion. Though this may not seem dramatic, one has to realize that scaling the beam linearly with n, implies an instrument volume scaling by n-cubed. For infrared instruments application of materials with a high index of refraction is possible, such as silicon (n = 3.42, n-cubed = 40) or germanium (n = 4.0, n-cubed = 64).

Germanium can be mechanically ruled to yield immersed gratings[12,13]. Alternatively, gratings in silicon can be produced using anisotropic etching, see ref. 14 and references therein. This is the approach we have adopted for TROPOMI-SWIR. In silicon, etching is roughly two orders of magnitude faster in the <100> plane of the silicon crystal than in the <111> plane. This results in grooves with an apex angle of exactly 70.52 degrees. Under proper illumination from the inside, a high-quality echelle immersed grating can be produced, as visualized in Figure 4.
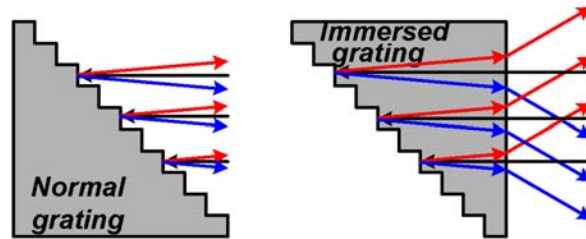

Figure 3: Comparison of a normal echelle grating (left) and an equally sized immersed grating (right).
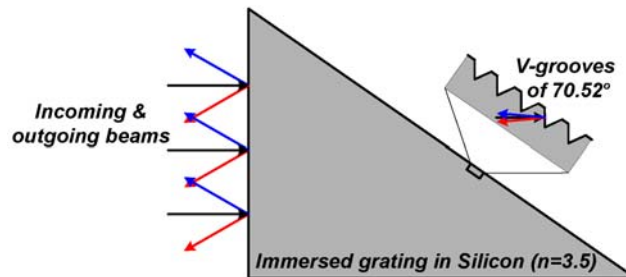

Figure 4: V-grooves produced by anisotropic etching with an apex angle of 70.5 degrees for a perfect echelle grating when illuminated from the inside in a Littrow geometry.

In a development program we have been able to produce gratings with a grating frequency of up to 667 lines/mm. A full wafer has been produced with a grating frequency of 232.6 lines/mm, in accordance with requirements for a TROPOMI-SWIR immersed grating used in 10th order diffraction, see Figure 5.

The wafer has been sawed and was bonded to a pre-cut silicon prism to form a complete immersed grating. The immersed grating was completed by applying an anti-reflection coating on the entrance/exit facet and an aluminum reflection coating over the grooves. The wave-front error of the immersed grating has been determined using a WYKO interferometer, both for the normal of the grating surface as well as for the reflecting grooves. The results of both reflections are given in Figure 6.
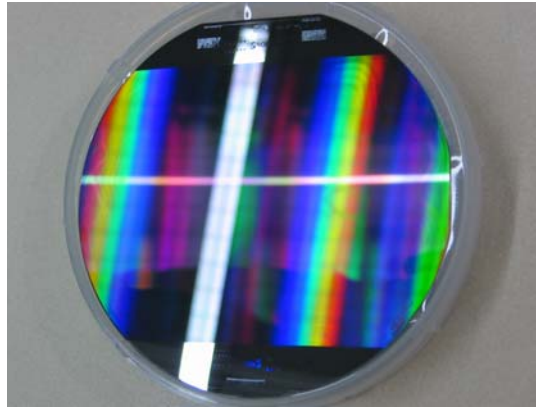
Figure 5: A full grating wafer with 232.6 lines/mm, etched in silicon, illuminated by the cleanroom ceiling lamp.
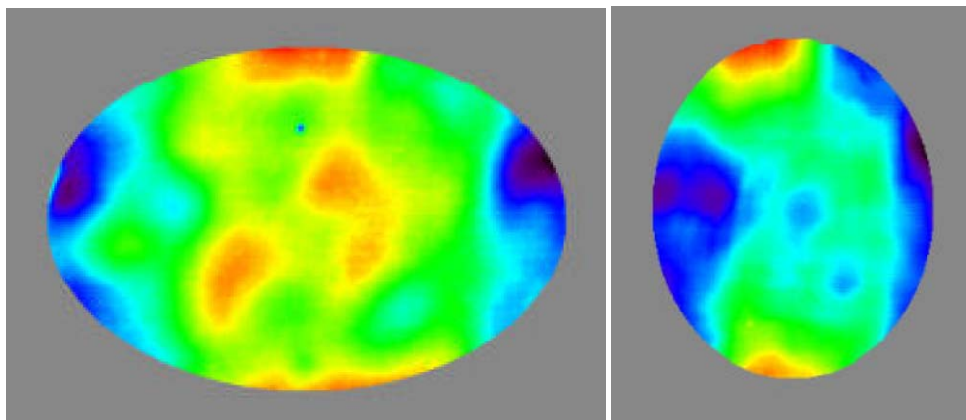

Figure 6: WYKO interferometer graphs of the wave-front error. Left: normal incidence reflection of the grating surface showing the non-flatness of the wafer. Right: reflection of the active grating-groove facets showing both the wafer non-flatness as well as all processing imperfections.

For normal incidence reflections the peak-to-peak wave-front error is 202 nm (39 nm rms), while for the reflections off the grating grooves the peak-to-peak error is 272 nm (47 nm rms). Although this is good enough for application in the breadboard model, it is certainly not the ultimate performance possible. Most of the wave-front error is now determined by the non-flatness of the wafer. Much better gratings can be obtained if the surface onto which the grating grooves are produced is optically flat. For this, we have just started processing grating grooves in silicon substrates of 50 mm thickness. These surfaces can be polished to 30 nm peak-peak non-flatness or better (lambda/20 at 633 nm). Also with optimization of the mask applied and the processing itself, it is expected that diffraction limited performance of the immersed grating is ultimately possible to achieve.

6.   CONCLUSIONS AND FUTURE WORK

The optical and mechanical design of the TROPOMI-SWIR channel has progressed to the level that a flight representative breadboard program could be started, where the optical design, as well as critical components are thoroughly tested. Critical components under test are the hybrid HgCdTe SWIR 2D detector array, the 2.3 µm LED calibration source and the silicon immersed grating. Goal of the breadboard model is to demonstrate functionality and performance of the TROPOMI-SWIR module by recording the ro-vibration transition lines of methane and CO in the 2.3 µm range, both in gas cell spectra as well as in atmospherical measurements.

The HgCdTe detector array will be tested for dark current, noise, linearity and uniformity.

The development program on immersed gratings yielded a device that was built from a grating pattern etched on a standard thin silicon wafer subsequently bonded to a silicon prism. The surface quality of this immersed grating is sufficiently high that the device can be used in the breadboard model.

For improved performance of the TROPOMI-SWIR flight model grating, a second development program was started that should yield monolithical immersed gratings.

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