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FROM OZONE MONITORING INSTRUMENT (OMI) TO TROPOSPHERIC MONITORING INSTRUMENT (TROPOMI)

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ABSTRACT

The OMI instrument is an ultraviolet-visible imaging spectrograph that uses two-dimensional CCD detectors to register both the spectrum and the swath perpendicular to the flight direction with a 115° wide swath, which enables global daily ground coverage with high spatial resolution. This paper presents a selection of in-flight radiometric and CCD detector calibration and performance monitoring results since the launch in July 2004. From these examples it will be shown that OMI is performing very well after more than four years in orbit. It is shown how the OMI irradiance measurement data have been used to derive a high resolution solar reference spectrum with good radiometric calibration, good wavelength calibration and high spectral sampling. The surface reflectance climatology derived from three years of in-orbit OMI measurement data is presented and discussed. The OMI mission may possibly be extended in 2009 for another two or four years, depending on the performance of the instrument. By 2013-2014 OMI on EOS-Aura and SCIAMACHY on ENVISAT will have reached more that twice their anticipated lifetimes. In order to guarantee continuity of Earth atmosphere tropospheric and climate measurement data new instrumentation shall be available around that time. A successor of OMI and SCIAMACHY, named TROPOspheric Monitoring Instrument (TROPOMI), scheduled for launch by the end of 2013, is discussed in this paper.

1. INTRODUCTION

The Ozone Monitoring Instrument (OMI) was launched on 15 July 2004 on NASA's EOS AURA satellite. The primary objective of the OMI instrument is to obtain daily global measurements of ozone and nitrogen dioxide in both the troposphere and stratosphere. The central science issues addressed by the OMI mission are the recovery of the ozone layer, the depletion of ozone at the poles, tropospheric pollution and climate change. In addition, OMI acts as the successor to the Total Ozone Mapping Spectrometer (TOMS) operated by NASA over the past 25 years. OMI has been producing valuable scientific data since its launch in July 2004 [1-4].

OMI combines a high spatial resolution (13x24 km^2, flight direction x cross-flight direction) and daily global coverage with a 2600 km wide swath on the ground. In this way tropospheric trace gases can be observed with high spatial resolution and cloud-free ground pixels are more easily obtained as compared to instruments with scanning mirrors. OMI routinely delivers absolutely calibrated spectral radiances and irradiances in the spectral range from 264-504 nm. These are used to retrieve the primary data products: ozone total column, ozone vertical profile, UV-B flux, nitrogen dioxide total column, aerosol optical thickness, cloud effective cover, cloud top pressure and secondary data products: total column SO_2, BrO, HCHO and OClO. The atmospheric constituent concentrations are retrieved from nadir observations of backscattered light from the sun on the earth's atmosphere in the ultraviolet-visible wavelength range (264-504 nm) using both Differential Optical Absorption Spectroscopy (DOAS) algorithms and algorithms that have been used before in the TOMS instrument series. The ozone profile is obtained from strong wavelength dependence of the absorption cross-section between 270 and 330 nm. Further details on the OMI design and calibration are given in [1]. The validation of the OMI level-1b radiance and irradiance data products is further discussed elsewhere [5].

OMI has been developed by Dutch and Finnish industry in close collaboration with the climate research and meteorological community and under contract with the Netherlands Agency for Aerospace Programmes (NIVR) and the Finnish Meteorological Institute (FMI). The Royal Netherlands Meteorological Institute (KNMI) is the Principal Investigator (PI) institute for the OMI instrument.

The TROPOMI instrument follows in the footsteps of OMI on EOS-Aura and SCIAMACHY on ENVISAT by combining (and improving on) the best features of these two instruments. The high spatial resolution of OMI is improved even further, while daily coverage is maintained. The OMI spectral range is extended to include a NIR band (680-775 nm) and a SWIR band (2305-2385 nm), which enables accurate measurements

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of cloud and aerosol properties and the climate gases CO and CH_4. The latter two gases can be measured accurately with sensitivity all the way to the ground. The scheduled launch date for TROPOMI is 2014, when OMI and SCIAMACHY expected lifetimes have been exceeded by (more than) a factor of two.

This paper describes and discusses a number of OMI in-flight calibration and monitoring results (radiometric, detector) in section 2, as well as the high resolution solar reference spectrum (section 3) and surface reflectance climatology (section 4) derived from OMI measurement data. The TROPOMI mission and instrument concept is presented and discussed in sections 5 and 6. Conclusions are given in section 7.

2. OMI RESULTS: IN-FLIGHT DEGRADATION MONITORING

OMI observes the sun once per day with a quartz volume reflectance diffuser. By using these measurements the instrument degradation (optics and detector) can be monitored. As an example figure 1 shows the in-flight observed degradation from launch to launch plus four years for the UV2 channel. From figure 1 it can be observed that the degradation is about one percent in UV2, a very low number for a ultraviolet-visible hyperspectral imaging spectrometer such as OMI.

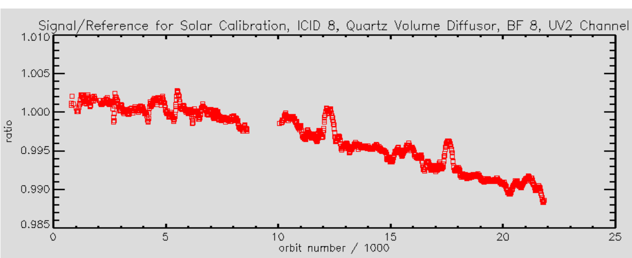

Figure 1: Observed instrument degradation in the UV2 channel from launch to launch plus four years for the sun over diffuser mode.

Figure 2 shows the measured signals from the on-board White Light Source (WLS) in UV2 for the same time period as figure 1. Variations in the order of 6 percent can be observed. However, it can also be observed that the measured output recovers at certain times. This can be understood from the fact that the WLS is used regularly (once per week) for not more than 20 seconds. This is too short for the quartz tungsten halogen cycle to stabilise, because the lamp does not reach thermal equilibrium. At certain times (around orbit number 10000 and 19180) the measured output increases considerably by about 6 percent. At these times the WLS was switched on for a duration of about 14 minutes. During this time the halogen cycle is operating properly and the lamp reaches thermal equilibrium. These processes seem to clean the quartz bulb from any residues, causing the lamp output to increase. This implies that the observed degradation in figure 2 mostly originates from the WLS itself, rather than from the instrument. When this lamp degradation (which can be recovered) is taken into account the observed instrument degradation in the UV2 channel is not measurable, i.e. less than one percent. Thus the WLS measurements confirm the results obtained from the sun measurements.

Figure 3 shows the measured signals from the on-board LEDs in the UV2 channel for the same time period as figure 1. A more or less linear decrease in the order of 5 percent can be observed. Combination of these results with the results from the sun and WLS measurements leads to the conclusion that the observed behaviour in figure 3 is caused by degradation of the LEDs themselves in four years time. The LEDs are used for about 3 minutes per day, so the total LED-on time in figure 3 is about 80 hours.

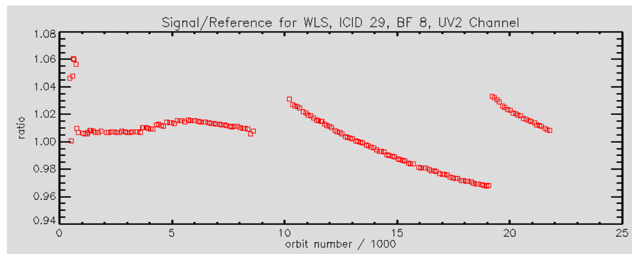

Figure 2: Observed instrument degradation in the UV2 channel from launch to launch plus four years for the WLS mode.

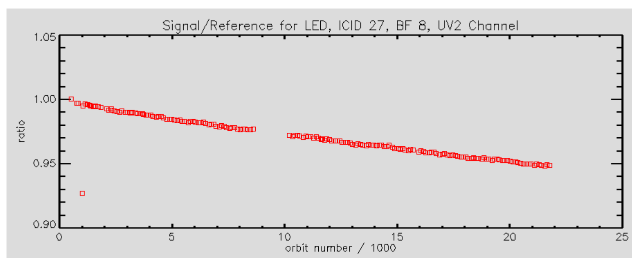

Figure 3: Observed instrument degradation in the UV2 channel from launch to launch plus four years for the LEDs.

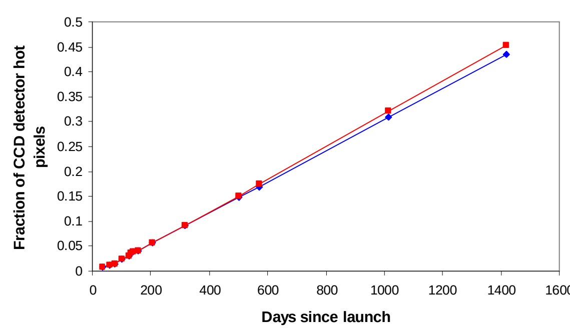

Figure 4: Number of unbinned CCD detector pixels impacted by radiation damage from launch to launch

plus four years. The blue curve is for the UV detector, the red curve for the VIS detector.

It is well known that CCD detectors are sensitive to in-flight radiation damage by high energetic (> 10 MeV) protons, mostly trapped in the magnetic field of the earth [1]. Figure 4 shows the behaviour of both CCD detectors from launch to launch plus four years. It can be observed that about 45% of the unbinned pixels shows changed behaviour as a result of radiation damage. This changed behaviour manifests itself in the form of increased dark current (up to a factor 10) and so-called Random Telegraph Signal (RTS) behaviour, where the dark signal of the pixel jumps between at least two quasi-stable levels [1]. By implementing a method of measuring and correcting for pixel-dependent variation in the dark signals by far the largest fraction of pixels affected by radiation damage can still be used for scientific purposes. After four years in orbit only about two percent of the binned pixels is affected too much by radiation damage and can no longer be used.

3. HIGH RESOLUTION HIGH SAMPLING RADIOMETRICALLY CALIBRATED SOLAR IRRADIANCE REFERENCE SPECTRUM DERIVED FROM OMI DATA

The OMI irradiance measurement data have been used to derive a high resolution solar irradiance spectrum with good radiometric calibration and with high spectral sampling. The OMI spectral slit functions have been accurately calibrated on the ground using a dedicated setup [6]. By convolving the high resolution solar reference spectrum with the measured OMI spectral slit functions and by comparing the result with existing lower resolution solar irradiance reference spectra with good radiometric calibration from the literature, the original high resolution solar reference spectrum can be radiometrically calibrated. The agreement on a 2 nm resolution grid of the new high resolution solar reference spectrum derived with OMI measurement data with most other solar reference spectra is within 4 – 5%. The derived high resolution solar reference spectrum has an accurate radiometric scale over the entire wavelength range between 250 and 550 nm, as well as a high resolution (0.025 nm) and sampling (0.01 nm), with an accurate wavelength scale of better than 0.002 nm over the whole wavelength range [7].

4. EARTH SURFACE REFLECTANCE CLIMATOLOGY DERIVED FROM THREE YEARS OF OMI DATA

Using three years of OMI data from October 2004 to October 2007 a global climatology of the earth's surface Lambertian Equivalent Reflectance (LER) has been derived with a temporal resolution of one month and a spatial resolution of 0.5° by 0.5° in the wavelength range 328 to 500 nm. As a result of the daily global coverage combined with the high spatial resolution is has been possible to use a histogram-based statistical method to derive the LER and to reduce the impact of clouds on the derived climatology with only three years of OMI measurement data. Figure 5 shows a number of histogram examples for different ground scenes. By analysing such histograms the LER can be determined accurately for each location on the earth as a function of season. For example, for clear ocean observations the higher values in the histogram along the horizontal axis correspond to (partly) clouded scenes, so the lowest value in the histogram is chosen as the LER value. On the other hand, for ice, snow and desert areas (narrow peak) the most frequent value in the histogram is selected as the LER value. Such analyses are possible when the histograms for all locations on the earth are available, which is possible with OMI data after only three years. Increasing the observation time in the future will improve the statistics of the histograms even further.

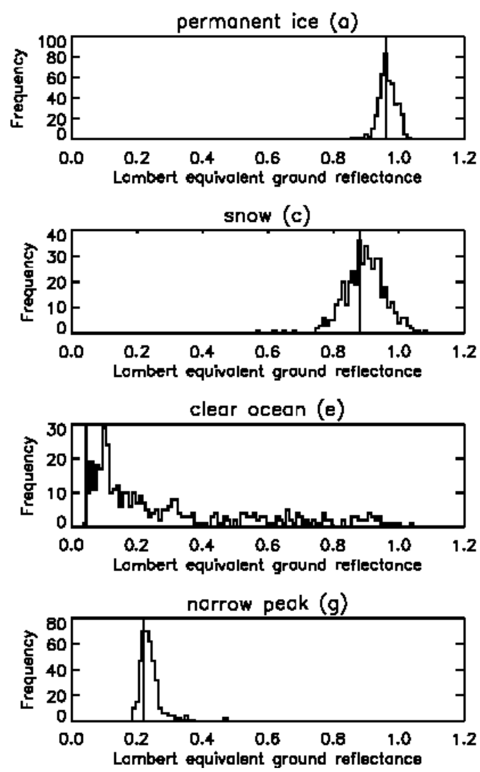

Figure 5: LER histogram examples for different ground scenes. The narrow peak corresponds to desert scenes. The vertical lines correspond to the most accurate LER value as determined from the histogram.

Figure 6 shows the resulting yearly minimum LER values as a function of geolocation and wavelength. It can be observed that the continents are darker than the oceans in the ultraviolet and (much) brighter than the oceans for desert and snow/ice areas at 500 nm. This is also shown in figure 7, which shows the spectral dependencies for a number of ground scenes as derived from the OMI data and the LER analysis. Figure 6 also shows the LER variations in the oceans at different geolocations.

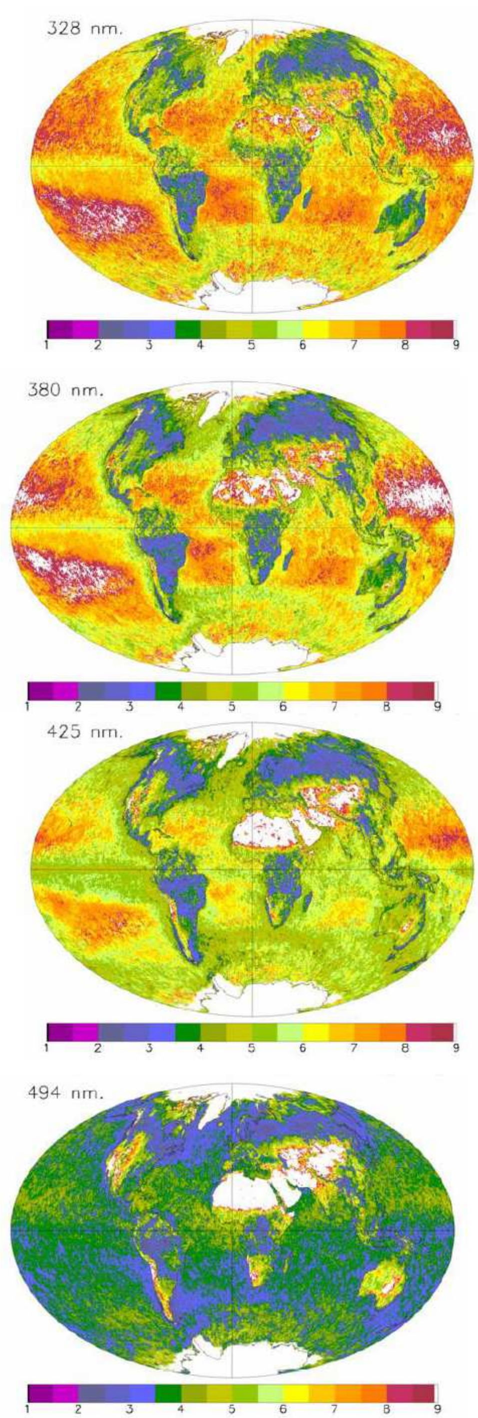

Figure 6: Minimum yearly LER as derived with OMI for the wavelengths 328 nm, 380 nm, 425 nm, 494 nm (top to bottom). White colour indicates values higher than the maximum value on the scales plotted below each figure.

The results agree reasonably well with earlier observations made by the Total Ozone Mapping Spectrometer (TOMS) and by the Global Ozone Monitoring Experiment (GOME). The overall accuracy of the OMI LER climatology is approximately 0.01 to 0.02 for the longer wavelengths and increasing towards the shorter ultraviolet wavelengths, as a result of stronger ozone absorption towards the ultraviolet. More details on the OMI LER are given in [8].

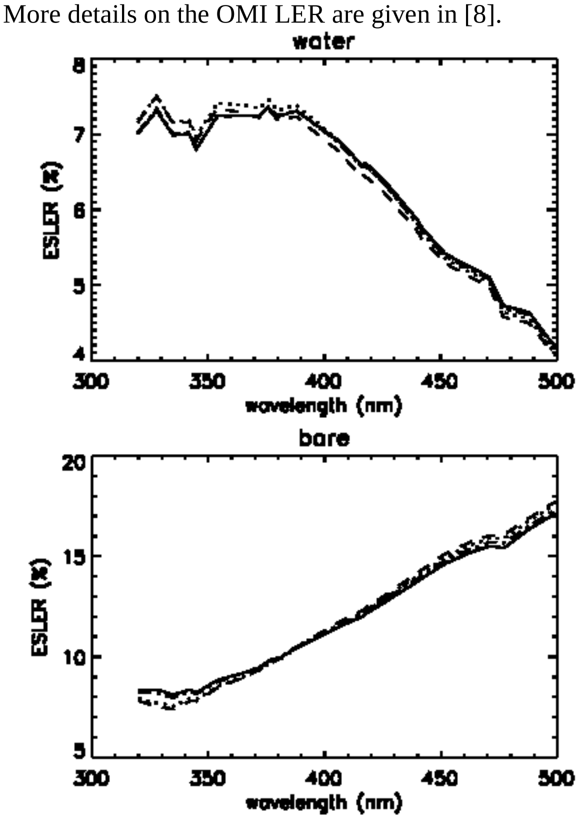

Figure 7: Two examples of the spectral dependence of the LER as determined from OMI measurement data for oceans (water, top) and for desert areas (bare, bottom). The different lines are the data for January (solid line), April (dotted line), July (dashed line) and October (dash-dotted line).

5. THE TROPOMI MISSION

After NASA's EOS-Aura satellite, carrying the OMI instrument, and ESA's ENVISAT satellite , carrying the SCIAMACHY instrument, no other instrumentation is planned in space with comparable capabilities as OMI and SCIAMACHY until the launch of GMES (Global Monitoring for Environment and Security) Sentinel 5 in 2019/2020. This means that from ultimately 2014 onward a data gap will exist in measuring the troposphere from space. The GOME-2 and IASI instruments on MetOp will not be able to cover this gap, due to their limited spatial resolution and lack of CH_4 and CO [9,10] measurements with good sensitivity down to the Earth's surface. For the above purposes the TROPOspheric Monitoring Instrument, TROPOMI, has been defined as the successor of OMI and SCIAMACHY and bridge the time period from 2014 until the GMES instrumentation.

TROPOMI will complement the observational records by OMI [1-5] and SCIAMACHY [11] and improve on their spatial resolution. The good spatial resolution combined with daily global coverage of OMI and the spectral range of SCIAMACHY are combined in TROPOMI. TROPOMI will also enable accurate mapping of anthropogenic and natural emissions on a global scale, for which it is essential that accurate measurements (i.e. with excellent signal-to-noise) of tropospheric constituents can be made with high spatial resolution. The objective to measure climate change and air pollution constituents requires measurements in a spectral range covering 270-2385 nm, which is what TROPOMI aims to do. As compared to OMI the TROPOMI is also expanded with a NIR optical channel in the wavelength range 680-775 nm. This enables accurate measurements of the O_2 A-band, which in turn enables accurate measurements of cloud and aerosol properties, that are essential for accurate retrievals of tropospheric air pollution and climate change constituents. In addition, a SWIR band has been added for CO and CH_4 observations.

The TROPOMI mission objective is to measure the troposphere for scientific research, and in support of services to society, down to the Earth's surface, with sufficiently high spatiotemporal resolution to quantify anthropogenic and natural emissions and atmospheric life cycles of trace gases and aerosol particles, which impact on air quality and climate forcing from the regional to the global scale.

Derived from this high-level mission objective the TROPOMI science objectives are:

- To better constrain the strength, evolution, and spatiotemporal variability of the sources of trace gases and aerosols impacting air quality and climate.
- To improve upon the attribution of climate forcing by a better understanding of the processes controlling the lifetime and distribution of methane, tropospheric ozone, and aerosols.
- To better estimate long-term trends in the troposphere, related to air quality and climate from the regional to the global scale, and provide boundary conditions for assessing local and regional air quality.
- To develop and improve air quality model processes and data assimilation in support of operational services, including air quality forecasting and protocol monitoring.

TROPOMI responds to the need of:

- A global observing system for climate change and air pollution.
- Monitoring tropospheric composition.
- Filling the data gap in the next decade.
- Understanding the composition of the troposphere and its variability.
- Mapping of anthropogenic and natural emissions on a global scale.

The TROPOMI instrument will fly on a spacecraft that will be in a sun-synchronous orbit, with a preferred altitude of 820 km and a 13.30 ascending node equator crossing local time. In such an orbit the VIIRS instrument on NPP/NPOESS can provide important sub-pixel cloud and aerosol information and an early afternoon orbit will improve the sensitivity of solar backscatter observations from space to the boundary layer because:

- air pollution in the afternoon is mostly more pronounced than during the morning hours.
- the depth of the boundary layer increases over the day.
- solar zenith angles are smaller in early afternoon.

Furthermore, in this configuration optimal temporal coverage is achieved with TROPOMI providing early afternoon data and MetOp morning data.

6. THE TROPOMI INSTRUMENT

TROPOMI is a push-broom type spectrometer that covers a spectral range from ultraviolet to visible and selected bands in near-infrared (UV-VIS-NIR) [12] and short-wave infrared around 2.3 μm (SWIR) [13]. The instrument consists of two modules: one for the UV-VIS-NIR wavelength range with four optical channels and one optical channel for the SWIR wavelength range. The spectral properties are listed in table 1.

The instrument is equipped with four two-dimensional 1kx1k Silicon CCD detectors for UV-VIS-NIR, operated at temperatures of 230 K, and one 1kx256 HgCdTe CMOS detector for SWIR, operated at a temperature of 135 K. One dimension on the detectors is used to image the spectral dimension and the other dimension is used to image the cross-flight track spatial dimension. The combination of two-dimensional detectors with a wide 108 degrees cross-flight track field of view enables Earth measurements with daily global coverage and high spatial resolution. The resulting ground pixel sizes for the various channels are given in table 2.

The UV-VIS-NIR optical bench temperature in orbit is 290 K, while the SWIR optical bench temperature is

reduced to 200 K in order to suppress thermal background signals to acceptable levels.
The UV-VIS-NIR and SWIR modules have separate, but very similar, telescopes. A polarisation scrambler renders the UV-VIS-NIR instrument insensitive to the polarisation state of the incident light. Such a polarisation scrambler is probably not required for the SWIR channel. The UV1 channel has a separate larger entrance slit than the entrance slit for the UV2, VIS and NIR channels. The SWIR channel also has its own entrance slit. The similarities in the telescopes and the spectrometers for the UV-VIS-NIR and SWIR modules enable good ground-pixel coregistration for all cross-track viewing angles.
Once per day the UV-VIS-NIR and SWIR modules will observe the sun via dedicated calibration units equipped with quartz volume diffusers. The solar irradiance measurements are used for normalisation of Earth shine measurements to obtain top of the atmosphere reflectances as well as for in-orbit monitoring of the radiometric and spectral instrument stability. For in-flight calibration and monitoring purposes the UV-VIS-NIR module is also equipped with LEDs and a White Light Source (WLS). The SWIR module is equipped with infrared LEDs for broadband illumination and an infrared laser module for monochromatic illumination.

Table 1: Definition of the spectral bands.

Spectral band	Spectral range [nm]	Spectral resolution [nm]	Spectral sampling [pixels]
UV1	270 - 320	0.90	3.3 - 3.4
UV2	295 - 380	0.40	3.4 - 3.6
VIS	360 - 500	0.50	3.3 - 3.6
NIR	680 - 775	0.35	3.2 - 3.6
SWIR	2305-2385	0.25	2.5 - 2.7

Table 2: Instantaneous ground pixel size.

Channel	Ground pixel size: flight x cross-flight direction [km^2]	Detector binning factor in cross-flight direction
UV1	21 x 28	8
UV2	7 x 7	4
VIS	7 x 7	4
NIR	7 x 7	4
SWIR	7 x 7	1

Besides high spectral resolution, wide spectral coverage from 270-2385 nm as specified in table 1, daily global coverage and high spatial resolution on the ground the TROPOMI instrument will perform measurements with high signal-to-noise, which enables accurate observation of minor (tropospheric) atmospheric trace species. The signal-to-noise values for the TROPOMI measurements for the radiance levels as shown in figure 8 for UV-VIS-NIR and for a radiance level of $4*10^{11}$ photons/(s cm^2 sr nm) for SWIR are given in table 3. For the UV-VIS-NIR the

Table 3: Earth radiance signal-to-noise for all optical channels.

Channel	Earth radiance signal-to-noise
UV1	100 (270 - 300 nm) 1000 (300 - 308 nm)
UV2	100 at 305 nm 300 at 310 nm 1000 at 320 nm 1000 (320 - 370 nm)
VIS	1500
NIR	100 (in absorption minimum) 500 (in continuum)
SWIR	70 (threshold) 150 (goal)

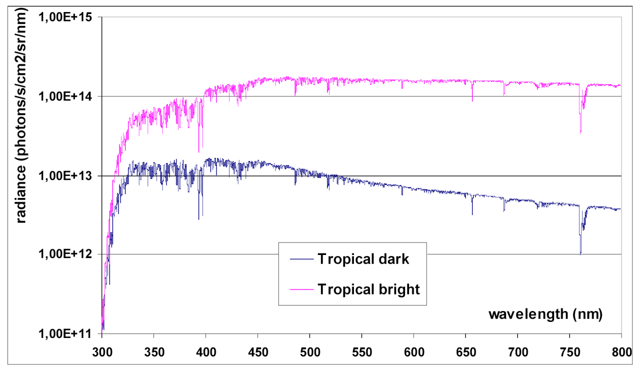

Figure 8: Reference radiance level for UV-VIS-NIR (blue). The pink curve is the highest radiance for which the UV-VIS-NIR channels shall not saturate.

Table 4: Remaining TROPOMI instrument parameters.

Mass	UV-VIS-NIR: 68 kg SWIR: 22 kg ELUs: 29 kg Total mass: 150 kg
Dimensions UV-VIS-NIR Dimensions SWIR Overall dimensions UV-VIS-NIR, SWIR, ELUs, thermal hardware and remaining parts.	44x40x42 cm^3 23x22x23 cm^3 70x70x60 cm^3
Power consumption	100 W (nominal) 150 W (peak)
Data rate	22 Mbps (nominal) 32 Mbps (peak)
Average data volume per orbit	13 GBytes

reference radiance level as shown in figure 8 corresponds to an illumination condition with low Solar Zenith Angle (SZA) and with a surface albedo of 2%. The SWIR radiance level corresponds to a SZA of 70 degrees and surface albedo of 5%. The nominal exposure times are 3 seconds in UV1 and 1 second in UV2, VIS, NIR and SWIR.

In addition, for TROPOMI similar in-orbit spectral stability and (long-term) radiometric stability are anticipated as for OMI. The spectral stability is expected to be in the order of 0.01 pixel over an orbit and any potential long-term radiometric degradation is expected to be smaller than 3% over the complete wavelength range from 270-2385 nm over the foreseen mission duration of five years. A number of remaining TROPOMI instrument parameters are given in table 4.

The cooling system for the optical benches and the detectors is a passive cooling system with a number of temperature levels. The SWIR detector is the coldest point with a temperature of 135 K. The SWIR optical bench is operated at 200 K. The UV-VIS-NIR detectors are operated at 230 K, while the UV-VIS-NIR optical bench has a temperature of about 290 K. The electronics boxes are also cooled at a temperature of about 300-310 K.

7. CONCLUSIONS

A number of in-flight calibration and performance monitoring results of the Ozone Monitoring Instrument (OMI), launched on 15 July 2004 on the EOS-AURA satellite, have been presented and discussed. The high resolution solar reference spectrum derived with the use of OMI irradiance measurement data was presented and discussed, as was the surface reflectance climatology derived from three years of OMI measurement data. It was shown that OMI performs very well after more than four years in orbit.

The successor of OMI on EOS-Aura and SCIAMACHY on ENVISAT, the TROPOspheric Monitoring Instrument (TROPOMI) is described and discussed in detail. TROPOMI combines the best design features of the OMI and SCIAMACHY instruments to provide high accuracy and sensitivity measurement data with high spatial resolution (7 x 7 km^2) and daily global coverage for detailed studies of the Earth's atmosphere with focus on the troposphere and climate.

8. REFERENCES

1. M. R. Dobber, R. J. Dirksen, P. F. Levelt, G. H. J. van den Oord, R. Voors, Q. Kleipool, G. Jaross, M. Kowalewski, E. Hilsenrath, G. Leppelmeier, J. de Vries, W. Dierssen, N. Rozemeijer, Ozone Monitoring Instrument calibration, *IEEE Trans. Geosc. Rem. Sens.*, 44 (5) (2006).

2. P. F. Levelt, E. Hilsenrath, G. W. Leppelmeier, G. H. J. van den Oord, P. K. Bhartia, J. Tamminen, J. F. de Haan, J. P. Veefkind, Science objectives of the Ozone Monitoring Instrument, *IEEE Trans. Geosc. Rem. Sens.*, 44 (5) (2006).

3. P. F. Levelt, G. H. J. van den Oord, M. R. Dobber, J. Claas, H. Visser, J. de Vries, The Ozone Monitoring Instrument, *IEEE Trans. Geosc. Rem. Sens.*, 44 (5) (2006).

4. G. H. J. van den Oord, J. P. Veefkind, P. F. Levelt, M. R. Dobber, Level 0 to 1B processing and operational aspects, *IEEE Trans. Geosc. Rem. Sens.*, 44 (5) (2006).

5. Validation of Ozone Monitoring Instrument level-1b data products, M. Dobber, Q. Kleipool, R. Dirksen, P. Levelt, G. Jaross, S. Taylor, T. Kelly, L. Flynn, G. Leppelmeier, N. Rozemeijer, J. Geophys. Res., 113, D15S06, doi:10.1029/2007JD008665 (2008).

6. R. Dirksen, M. Dobber, R. Voors, P. Levelt, Prelaunch characterization of the Ozone Monitoring Instrument transfer function in the spectral domain, *Applied Optics*, Vol. 45, no. 17, 2006.

7. The high-resolution solar reference spectrum between 250 and 550 nm and its application to measurements with the Ozone Monitoring Instrument, M. Dobber, R. Voors, R. Dirksen, Q. Kleipool, and P. Levelt, *Solar Physics*, volume 249, no. 2, 281-291, June 2008, doi:10.1007/s11207-008-9187-7.

8. Earth Surface Reflectance Climatology from Three Years of OMI Data , Q. L. Kleipool, M. R. Dobber, J. F. de Haan, and P. F. Levelt (2008), *J. Geophys. Res.*, doi:10.1029/2008JD010290, in press.

9. SCIAMACHY carbon monoxide total columns : statistical evaluation and comparison with CTM results, J. de Laat et al., J. Geophys. Res., 112, 2007, doi:10.1029/2006JD008256.

10. Evidence of long-range transport of carbon monoxide in the southern hemisphere from SCIAMACHY observations, A.Gloudemans et al., Geophys. Res. Lett., 33, L16807, 2006, doi:10.1029/2006GL026804.

11. SCIAMACHY, Monitoring the Changing Earth's Atmosphere, M. Gottwald et al., ed. M. Gottwald DLR, 2006.

12. TROPOMI: Solar backscatter satellite instrument for air quality and climate, J. de Vries et al., Proceedings SPIE Europe Remote Sensing, Florence (Italy), 17 - 20 September 2007.

13. Breadboarding activities of the TROPOMI-SWIR module, R. Hoogeveen at al., Proceedings SPIE Europe Remote Sensing, Florence (Italy), 17 - 20 September 2007.