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Martijn Brouwer

Robin van Buuren

Niels Gawlitta

Semen Grabarnik

et al.



OPTICAL COATINGS FOR THE TROPOMI UV CHANNEL

Martijn Brouwer¹, Robin van Buuren¹, Niels Gawlitta¹, Semen Grabarnik², Nick van de Valk¹, Rob Vink¹, Hedser van Brug¹, Huib Visser¹

¹ Netherlands Organisation for Applied Scientific Research (TNO), The Netherlands

² ESTEC, European Space Agency (ESA), The Netherlands

I SUMMARY

Earth observation measurements at wavelengths below 320nm are challenging due to the steep decrease of the earth irradiance towards shorter wavelengths. Stray light and ghosting of longer wave light can easily overwhelm the signals at short wavelengths. In the UV channel (270-320nm) of the TROPOMI instrument this challenge has been addressed using a number of coatings. Three black UV mirror coatings absorb light with a wavelength above 370nm. Together, these achieve more than four orders suppression of long wave out-of-band light. A low-pass transmission filter with a position dependent cut-off wavelength is deposited on the last lens surface, directly in front of the detector. At the position where short wavelength light passes the filter, longer wavelength in-band stray light and ghosts are blocked. A simulation predicts that this graded filter reduces ghosting by a factor 20 and scatter related stray light by factor 30.

II INTRODUCTION

The TROPOMI earth observation spectrometer will be the payload of the ESA Sentinel 5 precursor mission. This instrument will measure the concentration of various gasses in the earth atmosphere. TROPOMI optical system consists of a telescope, a calibration unit and four channels: UV (270-320nm), Uvis (320-495nm), NIR (675-775nm) and SWIR (2305-2385nm). An overview of the instrument design has been presented at ICSO 2012[1] while the current status and initial performance measurements are presented at this conference[2].

Compared to its predecessors, TROPOMI will be a big step forward in terms signal to noise ratio. Realisation of this big step forward is especially challenging for the UV channel that is used for ozone measurements. This is because the power of incoming UV light is very low compared to visible and near infrared light. Moreover, the power within the UV band drops quickly towards the short wave side. This is shown in Fig. 1: at 320nm, the boundary between the UV and Uvis band, the irradiance is an order lower than at the longwave side of the Uvis band, and within the UV band the irradiance of light coming from earth drops three orders of magnitude.

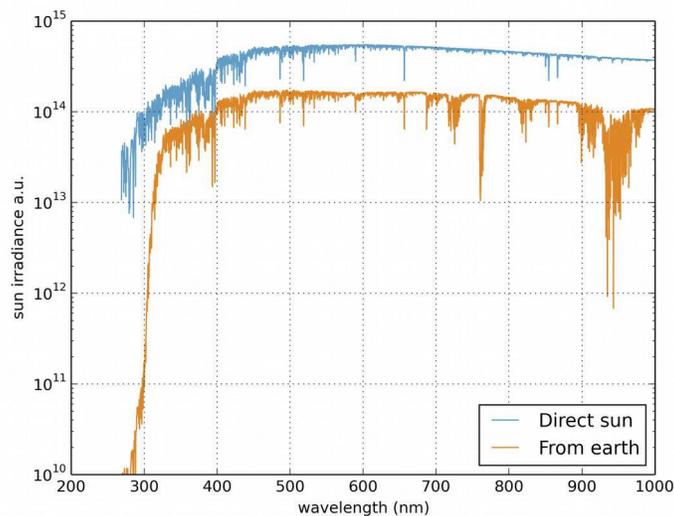


Fig. 1: Spectrum of sunlight as received directly from the sun (blue) and from earth (orange)

An overview of the UV channel optical components and the optical path is presented in (Fig. 2). The building blocks of the UV channel are:

- a reflective slit that is the optical interface with the telescope
- the UV-SWIR dichroic mirror, reflecting the UV band
- a collimator consisting of one lens (CL1) and four mirrors (M1 - M4)
- the grating

- an imager composed of the M5 mirror and three lenses (L1 - L3)

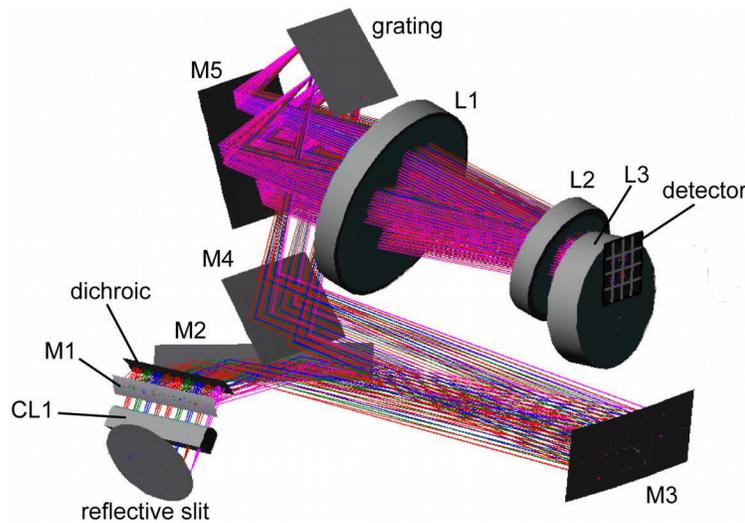


Fig. 2: Optical path of the UV channel

To suppress visible and near infrared light, minimise in-band stray light and reduce the intensity differences within the UV band special coatings have been applied:

- Out of band light from 370 – 1100nm has been suppressed using a black mirror coating on M1, M3 and M5.
- The in-band intensity variation has been reduced by the coatings on the five mirrors. The reflection of the five mirrors slowly decreases from 300 to 320nm.
- In-band stray light is strongly reduced by a graded filter coating on the last surface of the L3 lens. Because the UV L3 is close to the detector, the different wavelengths passing the last L3 surface are spatially separated. This separation is exploited using a shortpass filter with a position dependent cut-off wavelength. Advantage is that for measurements of short wavelengths stray light of longer in-band wavelengths is blocked.

The M2 and M4 mirror have a aluminium coating with a few enhancement layers.

III BLACK UV MIRRORS

The UV mirrors have been manufactured using single point diamond turning of phosphorous nickel plated aluminium bodies. Achieving the required surface shape and roughness is especially challenging due to the shape of the mirrors. The aspect ratio of the M1 and M2 is larger than 8. Moreover, the M2 and M4 are mounted a support at an angle of 45 degrees. Nevertheless a very low surface roughness has been achieved. After diamond turning the rms roughness was typically 0.8nm, which was reduced to 0.5 nm using a manual polishing step. These numbers are calculated from white light interferometry images after removal of spatial frequencies below 12.5/mm. This low roughness value is especially important to achieve a high UV reflection on aluminium mirror coatings such as the coatings of the M2 and M4.

A sketch of the design of the black mirror coating and a picture of a coated mirror are shown in Fig. 3. The basic building blocks of coating are a chromium based metal-dielectric absorber and a quarter wave reflection stack consisting of HfO_2 and SiO_2 . Matching layers are employed to reduce ripple in the absorption band. The coatings have been produced using e-beam evaporation. The greenish colour observed in the picture is caused by the high angle of incidence at which the picture has been taken. At a low angle, the coating has only has a very faint colour.

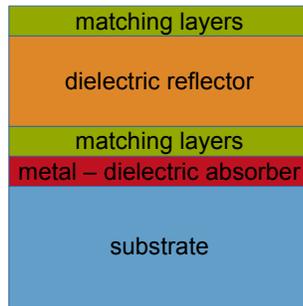


Fig. 3: Schematic overview of the black mirror design (left) and a picture of a mirror with the black mirror coating (right)

The reflection of one of the mirror coatings is shown in the left graph of Fig. 4. The in-band reflection from 270 to 305nm is 98.8% and decreases to 93% at 320nm thus reducing the in-band intensity variation. The reflection maxima in the 370 – 1100nm range are below 11%. The right graph shows the combined performance of the three black mirrors, one of which is adjusted for higher angles of incidence. Note that the maxima in the absorption band are well below 0.1%, which is achieved by shifting the extrema of the high angle coating relative to the other coating. Averaged over the 370-1100nm range, these three coatings provide a suppression of out-of-band light of 99.993%.

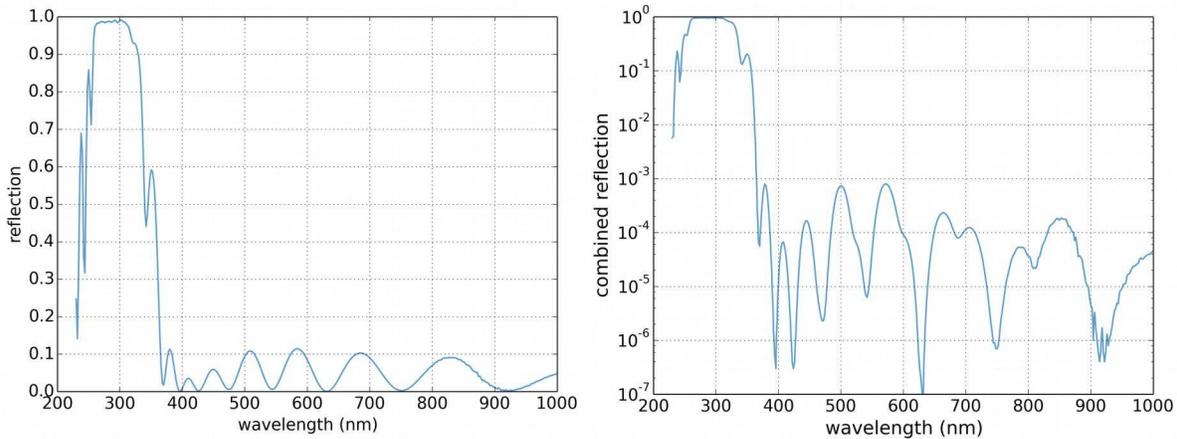


Fig. 4: Left: reflection spectrum of one the absorbing mirror coating. Right: combined performance of the three mirrors with an absorbing coating

IV GRADED TRANSMITTER COATING

The UV L3 lens is strongly curved concave asphere lens. The flat second surface it is coated with a graded transmitter coating. This short-pass filter consists of 32 layers and is based on a simple quarter wave stack with appropriate matching layers to the substrate. The filter has been produced using e-beam evaporation and is made of HfO₂ and SiO₂. The gradient has been produced using a carefully designed shadow mask. Only two iterations were necessary to produce the correct gradient.

The angle averaged transmission spectrum for three positions or transmitted wavelengths is shown in the left graph of Fig. 5. The steepness of the cut-off is limited by the range of the angle of incidence, which varies from 0 to 20 degrees. The transmitted wavelength for each of the three curves is indicated with a vertical line of the same colour. The graph shows that the transmission starts to drop some 10 nm from the transmitted wavelength. For the 270nm line, transmission is close to zero from 290nm, which means that in-band stray light from 290 – 320nm is effectively blocked. Given the strong wavelength dependence of the spectrum in incident light (Fig. 1), this means that nearly all in-band straylight is eliminated.

The right graph of Fig. 5 shows the measured position dependence of the 50% crossing point, together with lines of the minimum and maximum position requirements. The slope of the line is -2.5nm shift per mm, and the line is accurately in the middle between the lines of the minimum and maximum requirements.

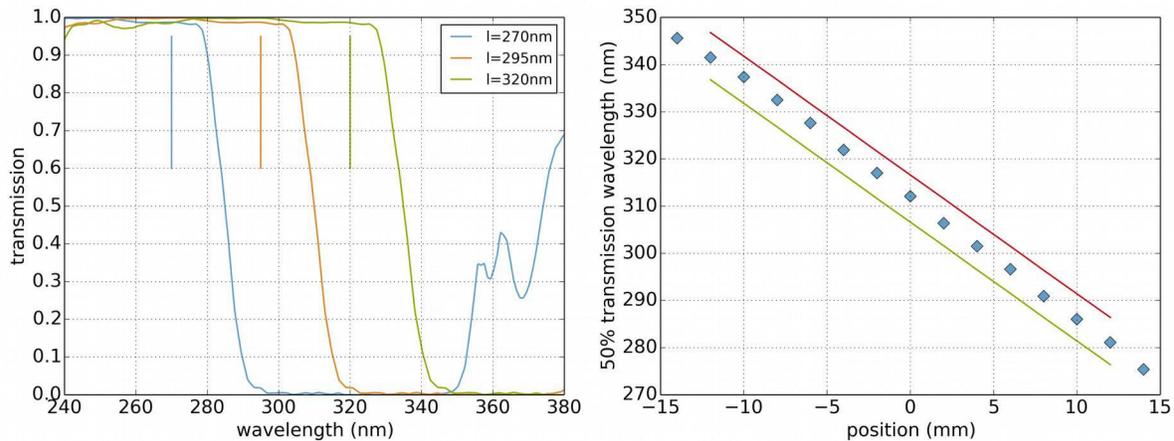


Fig. 5: Left: transmission spectrum of the graded coating at three positions on the L3 surface. Right: measured position dependence of the 50 % transmission point (blue dots), together with the required minimum (green line) and maximum (red line) position.

V RESULTS ON STRAYLIGHT PERFORMANCE

The effect of the graded transmitter coating on stray light due to ghosts and scattering has been estimated by ray-tracing using the ASAP[®] package. The UV channel was modelled from the slit to the detector. The measured reflection and transmission spectra of all mirrors and the L3 lens have been included in the model. For the other components realistic reflection and transmission estimates have been used.

The following stray light contributions have been modelled:

- Scattering due to roughness of the grating has been modelled using the Harvey-Shack model with the optimum parameters determined from the BRDF measurement on a representative grating.
- Scatter due to particulate contamination has been modelled using a BRDF function derived from Mie theory and particle size distribution function for cleaned optical surfaces. Contamination of the surfaces was determined to be approximately 400ppm.
- Surface roughness scatter has been included via a Harvey-Shack BRDF model normalised to TIS calculated using the smooth surface approximation. The surface roughness is assumed to be 1 nm for flat and spherical surfaces and 2 nm for aspherical surfaces.

Stray light simulations have been performed in ASAP for two cases: with and without graded transmission coating on the back of the L3 lens. The spectral dependence of stray light caused by scattering, and ghosts for these cases is shown in Fig. 6. All spectra are plotted relative to the signal strength, but in arbitrary units. Therefore, they give a qualitative impression of the stray light and ghost intensity throughout the UV band. The graphs show the levels of stray light caused by the surface roughness scatter, scatter from particulate contamination and ghosts.

The left graph in Fig. 6, without the graded coating, clearly shows that the effect of stray light and ghosting on the signal quality is much higher at the short-wave side of the UV band than at the long-wave side. The graph shows a number of high peaks at 280, 286 and 290nm, which are related to the high atmospheric absorption at these wavelengths and the corresponding low signal intensities.

With the graded transmitter coating included in the model (centre graph of Fig. 6), the picture is completely different. The relative intensities of the ghost and scattering contributions are much more uniform over the UV band and are in fact somewhat lower at the short-wave sides. This indicates the spectacular reduction of stray light and ghosting achieved by the graded transmitter.

The right graph in Fig. 6 finally shows the stray light and ghosting reduction achieved by the coating, calculated as the ratio between the spectra without and with graded coating. Above 305nm this ratio is nearly 1, as expected. At these wavelength the cut-off of the filter lies outside the UV band, and consequently, the filter does not reduce in-band stray light. Note that out-of-band stray light is eliminated by black mirrors and the dichroic mirror which reflection quickly drops above 320nm.

Below 295nm the effect of the filter quickly increases: at 270nm ghosting and scatter are reduced approximately by a factor of 20 and 30 respectively. These simulations demonstrate the large impact the graded transmitter coating will have on the accuracy of measurements in the UV band, and consequently on the ozone measurements that will be performed by the TROPOMI instrument. How big this impact is will become clear in the near future as the characterisation of the instrument proceeds.

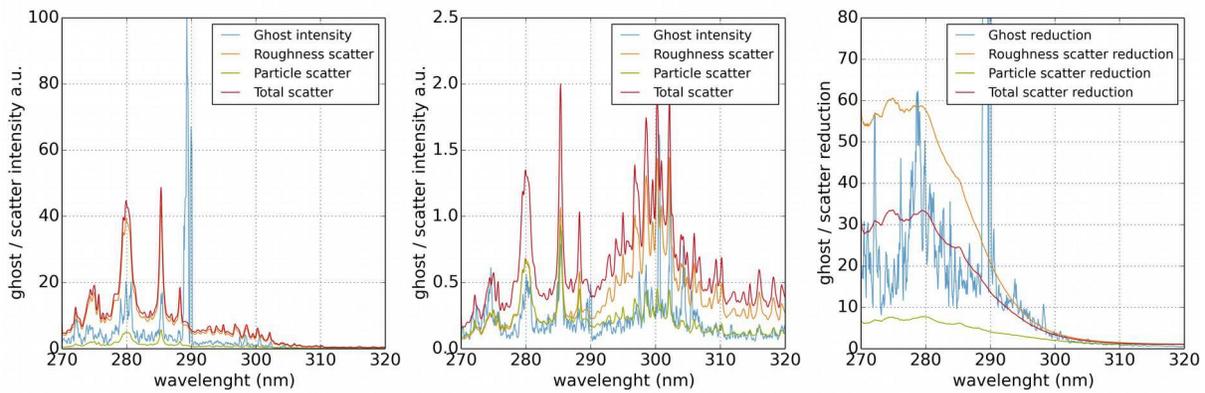


Fig. 6: Ghosting and straylight without (left) and with (centre) the graded transmitter coating. Note the difference in the scale of the y-axis. Right: ghosting and stray light reduction by the graded transmitter coating.

VI ACKNOWLEDGEMENT

TROPOMI has been developed for launch on the Copernicus Sentinel 5 Precursor satellite commissioned by the European Space Agency (ESA) and the Netherlands Space Office (NSO). Copernicus is a joint initiative of the European Commission and ESA.

Dutch Space is the prime contractor of TROPOMI. TNO and Dutch Space jointly develop the UVN module, including the UV channel, in an integrated team in which the complementary engineering disciplines of both partners are represented.

VII REFERENCES

- [1] R. Voors; J. de Vries; I. Bhatti; D. Lobb; T. Wood; N. van der Valk; I. Aben and P. Veefkind, "TROPOMI, the Sentinel 5 Precursor instrument for air quality and climate observations: status of the current design.", ICSO Proceedings 2012
- [2] J. Doornik; J. de Vries; R. Voors; J. Dingjan; B. Ording; N. van der Valk; R. Vink; R. Hoogeveen; J. Grant; T. Canas; Q. Kleipool and P. Veefkind, "The TROPOMI instrument, last steps towards final integration and testing", ICSO Conference 2014