Review comment amt-2019-488-RC3

Reviewer: **Rüdiger Lang**

Dear referee,

Thank you for your detailed review of our article. Our responses to your remarks, questions and considerations can be found in the table below. The performed changes to the manuscript are listed in the Section "Detailed Changes".

Response

Item	Referee comment	Author's response
Section 12/13	Section 12 and 13 describe the approach taken to correct for some partially significant, observed degradation effects especially in the UV. The overall approach seems sound (section 12). However it is not obvious for me how the degradation model approach and application in section 12 is related, or better decoupled, from the correction of the observed, partially quite significant offsets (up to 15%) in the absolute irradiance calibration of the solar port (section 13). My understanding from the paper is that the derived spectrometer component (from the 312 to 330 nm region) has been accounted for by a degradation correction, which is, again to my understanding, applied spectrally neutral to the full UV detector irradiance. Is this correction then also applied for Earthshine measurements, as one would expect it to be, because it is considered an effect of the common optical path? In case yes, I guess that the normalization day/orbit 2818/2819 is then used for an adjustment to OMPS, such that any likely degradation happening to the irradiance signals until this point is corrected for by reference to OMPS. Again, one expects an unknown degradation to have happened also to the Earthshine path until orbit 2818/2819, which would then lead to a differential degradation in reflectance after adjustment of the solar irradiance, and especially in case nothing is done additionally for the Earthshine	From the on-ground calibration we are sure that the irradiance calibration is not correct for bands 1-3 (made this clearer in the text). For the on-ground calibration of the radiance there is no such evidence. By setting the reference for the (spectrally smooth) diffuser degradation and the absolute irradiance adaptions on the same orbit, the diffuser degradation up to that point is taken into account. The spectral ageing in the UV spectrometer is corrected in radiance and irradiance for the entire mission. The spectral features already present in orbit 2818 are therefore removed and the smooth correction of the absolute irradiance takes care of the diffuser degradation. We made this point clearer in the text. If there is a remaining inconsistency in radiance this needs to be addressed in future validation for example via Earth targets, this has also been added to the text.

Item	Referee comment	Author's response
	data (and probably there are also some finite yet different accuracies for the radiometric key-data to be taken into account).	
Section 12/13	The choice of OMPS seems also very subjective. While it is stated that OMPS irradiance has been "independently calibrated", it is not stated what "independently" would mean in this context (without adjustment to reference spectra? If yes, then this should be stated). I would maintain that it remains just a choice. The results show a close to 3% difference with the Dobber et al. spectrum after adjustment. In contrast, all three GOME-2 instruments shave shown smaller residuals than 3% to the Dobber reference spectrum, above 300 nm at the beginning of live, without (!) adjustment (so using the on-ground derived key-data only). So this choice of a reference solar spectrum would leave a potential unknown "offset" of 2 to 3% with respect to other instruments and their absolute calibration after degradation correction. Since 2 to 3% accuracy is effectively the current limit on the knowledge of the solar irradiance accuracy in the UV and VIS wavelength region in general, such a choice for sure can be made, but it should be presented as the limit of the knowledge in the absolute calibration accuracy then also for this mission. Moreover, this would then also be the limit of knowledge on the Earthshine radiance accuracy, with a potentially even larger error on the reflectance. In this respect, the question is why an independent Earthshine degradation modelling has been ruled out. For previous missions GOME-1, 2 and SCIAMACHY degradation modelling using global averages of cloud free Earthshine data showed quite some success, and also Libyan desert degradation modelling should not be ruled out.	We made clearer in the text why OMPS was chosen. The idea was to be able to relate the changes to a single instrument and not a composite spectrum. And indeed, eventually it is a choice. We added a clarification on validation using Earth targets, this is future work. Therefore we are also not presenting any updated numbers for the radiance and reflectance accuracy yet.
Section 12	Finally, the derived spectrometer component in Section 12 seems to be on the order of 1% per 1000 orbits (Figure 11). In contrast the observed WLS and LED signal degradations seem to be lower or on the same order. I am wondering why the use of the internal light sources then have been ruled out for degradation monitoring or even correction, or how their "output degradation" could have been identified as such, when the identified spectrometer component is on the same order or even more significant. Is there an optical component in the path (like another folding mirror) between the spectrometer and the WLS, such that any direct Earthshine degradation modelling using these sources cannot easily be	Analysing WLS data has given valuable insight on the spectral ageing in the UV and the spectral overlap with UVIS. The light path of the WLS includes additional optics and is not identical to the Sun or Earth path. When using WLS for calibration purposes WLS features could be introduced into the L1 radiance/irradiance.

Item	Referee comment	Author's response
	done? It might be interesting to look at the ratio of calibrated SMR and calibrated WLS, and their (differential) evolution over time and spectrally in this context.	Added an explanation to the difference in light paths for DLED and WLS
Section 3, l 80ff	How exactly non-linear is the observed decrease of the light sources and can this decrease be attributed to the sources or is it already part of the optical chain for WLS? It should not be ruled out that this is simply a consequence of the spectrometer degradation observed in Section 12 (see before).	The decrease in signal can be caused by the source itself, the source's specific optical path and the instrument. Clarified this in the text.
Section 5, l.90ff	I would assume the temperature dependency of the dark current has been measured on-ground. From these measurements it could be stated here what is the projected dark current orbital dependency using the observed orbital detector thermal stability from HKTM.	The temperature dependency of the dark current has not been measured on-ground.
L.110ff:	The change in the gain during manoeuvres is not further explained. Can any reason be given for this?	So far no reason has been found to explain this behaviour. All available housekeeping parameters have been checked but no correlation was found.
l. 145ff	It would be interesting (and helpful for future missions) to get an idea (statistically) on the extend of blooming in pixel space. E.g. by providing a histogram (or table) on the number of occurrences over the number of pixels affected per event. Does such a statistic exist?	We have added numbers for the occurrence of pixel saturation. For the blooming itself a full statistical analysis is possible once version 2 of the L01b processor is active.
Section 8 on geo-referencing	Has any attempt be made for geo-rectification using VIIRS data? This should provide very accurate geo-referencing knowledge also on the point-spread function. Can anything be said about the alignment of the other bands not used in the geo-referencing analysis? Or can some qualitative assumption be derived from the optical setup (telescope) and alignment? A discussion would be needed here I think.	We have not attempted any cross-validation of the geolocation with VIIRS or other satellites. Considering the limited spatial resolution of TROPOMI we don't think that a comparison to higher resolution instruments would have added to the results. A discussion on qualitative assumptions for the other bands has been added.
Section 10 on slit irregularities	From Figure 6 it looks like the WLS exhibits significant spectral structure. Why is this? Actually, wouldn't a highly structured spectrum like the solar lead to a better correction?	Figure 6 is an irradiance image showing characteristic spectral lines. The data has been corrected with key data derived from WLS data.
Section 11 on goniometry	The azimuthal maximum variation of the sun should be reported in this Section in order to motivate/justify the restriction to 10 degrees, even though 15 degrees have been measured. Is the orbit stabilized, and for how long in the mission? Or in	The natural solar azimuth range during solar calibration measurements over one year is between -10° and +6.0° (range is 16°) for an ANX MLST of 13:30, which is the current mission requirement. The

Item	Referee comment	Author’s response
	other words, is there any restriction in future ground track drifts concerning the validity range of this data?	instrument requirements were therefore set to allow for measurements in the range -10° to +10° in azimuth and -4.25° to +4.25° in elevation. In reality the solar baffle allows light for a larger range, the measurements were therefore performed at the largest possible range achievable with the platform. The orbit is stabilized and follows Suomi NPP with a 3 to 5min delay. For nominal operations the solar port should not run out of its calibrated range. Furthermore the irradiance measurements are performed around a fixed azimuth angle using the reaction wheels. This is explained in Section 14, we added a reference to this and a sentence on the natural azimuth range.
Section 11	Section 11, on the origin of the remaining residuals in the goniometry key-data derived in-flight: I would guess that they are probably a combination of diffuser features, speckles, and especially instrument drifts between individual measurements and the temporal position of the normalization measurement. In addition, one should find the pattern of the observed degradation correction residual in such a potential drift, I would assume. Since the measurement period was quite long (400 orbits), and it was in an early state of the mission, can effects like gain drifts during this period, and as reported in the earlier sections, be ruled out? It would be good to discuss the status of the mission at the time of the dedicated measurement period (start orbit, overall platform thermal stability etc...), and if the measurements have been filtered for outliers.	The remaining residuals are - as you observe - connected to the residuals observed in the degradation correction. Added a clearer reference to the residual discussion in Section 12. Thermal effects can be excluded, the instrument was thermally stabilized since very early in the commissioning phase. The main part of electronic gain drifts is corrected by the use of the normalization measurements. Added start orbit, remark on electronic drifts and in Section 2 a remark on thermal stability for the measurements.
Section 12, degradation model:	Why would one expect that all components are “perfectly exponential”. At least in the long-run. Since this is not what is observed with other instruments, and for sure not in case of a potential mirror contribution. Is there a long-term trend observed in the Rk and Pk components?	Until now an exponential function was found to be the best fit. If this changes in the future we can adapt it. Added this remark to the text.
l. 364	“but especially in the UV range it is unclear if it is reliable”: Which spectrum is referred here to? Since we have observed that the Dobber et al., spectrum shows	That is the difficulty with inter-instrument comparisons, in the end it is a matter of choice. We

Item	Referee comment	Author’s response
	clearly better results for GOME-2 for wavelength below 300 nm at the beginning of the mission and without any adjustments than all other available reference spectra. I fear that at this stage this is no discussion about the truth, but probably more about inter-instrument consistencies.	tried to base our choice on how comparable the spectral resolutions and ranges are and that the we are traceable to a single instrument and not a composite. This point was made clearer in the text.
General:	Although it has been describe multiple times elsewhere, a table of band numbering associated with source region "UV", "UVIS, "NIR" "SWIR" and associated wavelength ranges would be of help for the reader to have at hand up-front. Since band numbers, detector labels and source regions are used multiple times in exchangeable ways in the paper.	This has already been adapted following the initial review comments.
Figure 5/6	"...within the requirements" -> add black lines in brackets p. 10ff: The plots in Figure 6 and the reported row numbers in the text (e.g. line 208) are different. The caption indicates the Figure shows the binned count. Somewhere at least a written translation should be made. E.g. in the caption: bin x corresponds to pixels yy. Or similar.	This has already been adapted following the initial review comments.
p14, ;l263:	Check sentence: "For double processing, so (?) ..." l.380 switch -> with	This has already been adapted following the initial review comments.

Detailed changes

List of changes to version 2

The page and line numbering in the Table below is according to version 2 which was public on the discussion page. The comments on the version 1 (the one which was initially sent out to the reviewers) have already been included in version 2.

Item	Change
New figure	Added new figure and caption at the beginning of the article. It shows a functional schematic of TROPOMI. Added a reference to this figure in several places in the text.
Fig 1-3, 5-9, 11-22	Enlarged plots or adapted plots to increase fontsize and improve readability. Adapted captions and the references to the plots accordingly. For Fig.1 added “The triangles in the top panel show the gain ratio as derived from on-ground measurements.”
p 1 l 13, abstract	Changed "processing from 2020 on" to "processing from late 2020 on".

Item	Change
p 1 l 22/23, Table 1	Adapted to be consistent with official PRF: 5.6-> 5.5, 7.2 ->7, 28.8->28
p2 l 27 ff	Replaced "The instrument is measuring the radiance on the day side of each orbit and once a day the irradiance via a dedicated solar port as described in detail in KNMI (2017) and Kleipool et al. (2018)." By " The instrument is measuring the radiance on the day side of each orbit and once a day the irradiance via a dedicated solar port as shown in Fig.1. Sun light passes through one of the two internal quasi volume diffusers (QVD1 and QVD2) and is coupled via the folding mirror into the telescope of the instrument. A detailed instrument description canbe found in KNMI (2017) and Kleipool et al. (2018)."
p 2 l 41, introduction	Changed "The timing and definition of the different orbit types was adapted to match the detected darkness of the eclipse. " to "The timing and definition for the measurement sequences of the different orbit types was adapted to match the detected darkness of the eclipse. "
p 3 l58	Added " All measurements described in this article were performed at the nominal temperatures with active thermal stabilization."
p 3 l 62	Added "when the radiant cooler points in a sub-optimal direction"
p 4 l 75 ff	Replaced "output" by "observed signal"and "detector response".
p 4 l 86	Added "Depending on the source and its location in the instrument, the listed values can contain contributions from degradation of the source, its specific optics, the diffusers, the folding mirror, the telescope and the spectrometers."
p 6 l 114	Added "or other housekeeping parameters" .
p 7 l 138, 141	Added " in the tropics". Changed "and" to "-". Added " In the tropics typically about 0.2-0.5% of the pixels are flagged for saturation in bands 4-6, other regions and bands are hardly ever affected."
p7 l 140	Added: " For the CCD detectors spatial binning is applied: the charge of several successive detector rows is added in the register and then read out."
p 7 l141	Replace "this" by "the saturation issue"
p 8 l143	Added:" (spatial direction)"
p 9 l157	Added: " ..., so only a narrow spectral range is available per UVN band."
p 10 l 183ff	Changed "For the SWIR and UVIS detectors the same effect is observed, so a mechanical change within the instrument during launch seems unlikely." to "For the SWIR, UVIS and NIR spectrometers the same effect is observed, so a mechanical change within the instrument itself during launch seems highly unlikely. For UV the signal to noise of the high resolution measurements with their small spectral range is too small to draw conclusions. The light for the UV and SWIR takes the same path up to and including the instrument slit and the UV spectrometer is part of the UVN optical bench as shown in Fig. 1. As the SWIR spectrometer shows the same effect as the UVIS and the NIR spectrometers and no difference is observed between UVIS and NIR, due to the instrument design it is highly unlikely that the UV spectrometer should behave differently."
p 10 l 188	Added " A further validation is not foreseen, as the nominal radiance measurements have a larger groundpixel size."

Item	Change
p 11 l 204	Added "or data for other bands becomes available"
p 11 l 208	Added "(spatial direction)"
p 11 l 210	Changed " Therefore not the main instrument slit but the slit in the UV spectrometer is most likely causing the feature. " to " From the instrument design as shown in Fig. 1 it can be seen that not the main instrument slit but the slit in the UV spectrometer is most likely causing the feature."
p 11 l 214	Added "as shown in Fig. 1"
p 11 l 217	Added " (columns)"
p 12 l 236	Changed "400 orbits" to " 400 consecutive orbits (starting in orbit 1247)"
p 13 l 241	Added " possible electronic drifts"
p 14 l 261	Added "The fitting window covers the natural yearly solar azimuth variation for the reference orbit with equator crossing time of 13:30 local solar time."
p 14 l 263	Changed " see also Section 12"to "see also Section 12 for the description of the residuals"
p 15 l 272	Added "The slew manoeuvres are included in the nominal operations baseline as described in Section 14. This reduces the measured azimuth range to less than ±1 ◦ around the reference angle."
p 15 l286 ff	Changed to "To determine relative electronic drifts, the DLEDs which are situated close to the detectors are used. The optical path of the WLS includes additional elements which are not part of the optical path for light from the Earth or the Sun, and the WLS light does not pass through the QVDs. The internal light sources also show a decrease in output which cannot be separated from instrument degradation as described in Section 4. The internal light sources are therefore less suitable for the calibration of the degradation of the irradiance and radiance optical paths.
p 15 l 287	Changed to "Radiance measurements in general show much variability in themselves and would require too much input from atmospheric models to be useful for the derivation and regular update of an independent and sufficiently accurate degradation correction for operational L1b processing. In the future the derived correction needs to be validated by - for example - using sites with well known reflectance."
p 15 l 291	Changed from "the degradation of the diffusers (QVD1 and QVD2) used for irradiance measurements, a gradual spectrally dependent increase of the throughput in the UV spectrometer and a drift of the CCD gain for the UVN spectrometers." To "the degradation of the diffusers (QVD1 and QVD2) used for irradiance measurements, a drift of the CCD gain for the UVN spectrometers and a gradual spectrally dependent increase of the throughput in the UV spectrometer. This spectral ageing in the UV spectrometer is observed for irradiance, radiance and WLS data and cannot be found in on-ground data."
p 16 l 300	Changed "composed" to "modelled"
p 16 l 304	Changed "perfect" to "are best described"

Item	Change
p 16 l 315	Added “For UVN (SWIR) a super pixel stretches over 20 (12) rows in the spatial direction. In the spectral direction (columns) it is 5,10,20 and 20 pixels for UV, UVIS, NIR and SWIR respectively. Apart from the spectrometer degradation in the UV, the data is spatially and spectrally smooth, so the super-pixel size has no impact on the result apart from noise reduction.”
p 16 l 316	Added “Following the postulate of the model, the”..
p 16 l 318	Added “If the residuals show in the future that the assumption of exponential decay is not justified anymore, a different fitting function can be used.”
p 16 l 333ff	Rephrased to “ In the left part of Fig.13 it can be seen that this spectrometer ageing is stronger than the signal decrease due to the diffuser degradation. In this way the UV spectrometer ageing nullifies the diffuser degradation.”
p 17 l 347	Added “diffuser”
p 17 l 349	Added “The spectrometer specific degradation Dspec in the UV spectrometer is derived for the entire mission so far and the correction is applied to both the radiance and irradiance. The correction is also applied to the reference orbits for the absolute irradiance calibration”
p 17 l 350	Added “ and that the steps occurring in the data around updates are minimal.”
p 22 Table 4	Changed “The degradation per band per 1000 orbits as determined up to orbit 9748” to “The mean degradation per 1000 orbits as determined up to orbit 9748.” Added % to the header.
p 23 l 362	Added “An investigation of various on-ground illumination sources via the Sun and the Earth port showed that the discontinuity is exclusively observed for the absolute irradiance calibration with the FEL lamp. The absolute radiance calibration with the FEL lamp is consistent with other calibration sources.”
p 23 l 364	Added “The correction to the absolute irradiance is derived for orbits 2818 (QVD1) and 2819 (QVD2), the same orbits the diffuser degradation is tied to. The UV spectrometer specific degradation has been corrected in the used data, see Section 12.”
p 23 l 365	Changed “A well-known solar reference is the high resolution Dobber spectrum (0.014 nm per pixel) (Dobber et al., 2008) and the Kurucz spectrum (Chance and Kurucz, 2010), which are high resolution composites of different solar measurement campaigns. It covers the spectral range of the TROPOMI instrument, but especially in the UV range it is unclear if it is reliable.” To “Well-known solar references are the high resolution Dobber spectrum (±0.014nm per pixel) (Dobber et al., 2008) and the Kurucz spectrum (Chance and Kurucz, 2010), which cover the spectral range of the TROPOMI instrument. They are both high resolution composites of different solar measurement campaigns and not based on a single instrument.”
p 23 l 375	Removed “independently calibrated”
p 23 l 376	Added two references: Seftor et al., 2014; NASA Goddard Space Flight Center, 2019
p 23 l 380	Replaced “spectral”by “radiometric”
p 24 l 402	Added “Adapting only the irradiance calibration for UV and UVIS changes the reflectance for these spectral ranges. Initial validations tests show that this has indeed a positive impact on the L2 retrievals. In the future a more extensive re-assessment of the radiometric accuracy can be performed and any potentially remaining inconsistencies in radiance and irradiance can be addressed.”

Item	Change
p 24 l 423/424	Adapted SSD to be consistent with table: 5.6-> 5.5, 7.2 ->7, 28.8->28
p 25, l 434/ 436	Changed v1 / v2 to version 1 /2
p 449	Changed “radiometry” to “radiometric”
References	Removed urls where doi is present, removed doi prefix in bib-file.
Language	Removed phrase “corrected for”.

Changes to initial version 1

The changes below have been performed to the initial version 1 sent out to the referees. These changes were already included in the version 2 which was published on the discussion page and are listed below for completeness.

Line number Fig/Table (version1/version2)	Original (version 1)	Update (version 2)
/Table 1		Added table on main characteristics.
24/ 24		Added " The main characteristics of TROPOMI are listed in Table 1. "
23/23	5.5km x 3.5km	Put non-rounded number to be consistent with new table: 5.6km x 3.6km
420/423	“before it was approximately 7 km at nadir and it is now about 5.5 km. In across-track direction the minimal sampling distance at nadir is around 3.5km for bands 2–6, about 7km for bands 7–8 and around 28km for band 1.”	Put non-rounded number to be consistent with new table: “before it was approximately 7.1km at nadir and it is now about 5.6km. In across-track direction the minimal sampling distance at nadir is around 3.6km for bands 2–6, about 7.2km for bands 7–8 and around 28.8km for band 1.”
Caption Fig.5/Fig.5	“The differences for low and high row numbers are now mostly within the requirements and more symmetrical.”	Added "(black lines)": “The differences for low and high row numbers are now mostly within the requirements (black lines) and more symmetrical.”
208	335-–337	Changed to em-dash: “335–337”
Caption Fig.6/Fig.6	"Note that the row numbering is showing the binned count."	Changed to " Note that the binned row count is shown in the plots, the affected detector rows are rows 335--337."

Line number Fig/Table (version1/version2)	Original (version 1)	Update (version 2)
220/221		Added: "Detector rows 335 and 336 correspond in this example to the binned row counter 144."
263/265	"For double processing, so re-analysing data that is corrected with the derived relative irradiance CKD, the standard deviation reduces to the order of $\times 10^{-4}$, this is an order of magnitude better than what was achieved with the on-ground data."	Re-phrased to: "To validate the integration of processor and key data, double processing is performed: data that has already been corrected with the derived CKD is re-analysed for remaining effects. Double processing irradiance data with the derived relative irradiance CKD reduces the standard deviation to the order of $\times 10^{-4}$. This result is an order of magnitude better than what was achieved with double processing of the CKD derived from on-ground calibration data."