Response to RC1 by Reviewer 3:

We would like to thank the reviewer for performing a thorough review and for the many helpful suggestions to improve our manuscript.

Below, we respond to each of the review comments. For the sake of clarity, the review comments are given in blue italics and our response is printed in normal font. Changes to the manuscript are printed in green.

This paper presents a new method to extend the typically used surface LER with a direction dependency. The DLER concept is applied to GOME-2 measurements, and the relation with the surface BRDF is analyzed both theoretically and practically. This paper is well-organized and well-written, and the content is of interest to the community involved in satellite retrieval of atmospheric properties. I recommend publication in AMT after the authors address minor comments below.

P1 L21 Please give the full names of the different species.

We think the chemical notations should be kept because of consistency with the rest of the paper. We propose to give the full name plus chemical notation if the name is not straightforward.

So, we have changed the sentence into:

" This includes the retrieval of trace gases such as ozone (O_3), nitrogen dioxide (NO_2), bromine oxide (BrO), formaldehyde (CH_2O), water vapour (H_2O), carbon dioxide (CO_2), carbon monoxide (CO), and methane (CH_4), and of cloud and aerosol information. "

P2 Could you also comment on the pros and cons of the Loyola et al., 2020 method with respect to DLER?

The text has been rewritten and a more extensive discussion of (and comparison with) the GLER and GE_LER databases is now provided in the updated version of the manuscript. Here we also take into account the review comment CC1 by Diego Loyola. The text now reads:

" Recently, several different approaches have been introduced to address this issue. One example is the introduction of geometry-dependent surface Lambertian-equivalent reflectivity (GLER) [Vasilkov et al., 2017; Qin et al., 2019]. In the GLER approach, surface BRDF information from the MODIS surface BRDF database [Gao et al., 2005] is used to calculate Lambertian surface albedo at 466 nm for land-covered satellite footprints of the OMI instrument. The result is a Lambertian surface albedo, ready to be used in a radiative transfer code with Lambertian surface reflection, calculated for the exact scattering geometry of the OMI footprint and for the specific date of the OMI footprint. The advantage is that this Lambertian surface albedo is adjusted to the geometry of the observation, whereas the surface albedo available in the typical Lambertian surface albedo climatologies is more representative for the minimum value of the surface reflectivities that were observed [see e.g. Lorente et al., 2018; Liu et al., 2020] – and therefore underestimates the surface albedo for many of the scattering geometries. The disadvantage of the GLER approach is that it, at least for land-covered scenes, depends fully on the MODIS surface BRDF database. This limits the spectral usage to the seven wavelength bands of the MODIS BRDF product. For the retrieval of NO_2 and of cloud properties from the O_2-O_2 band, both performed in the spectral regime close to 466 nm, this is not a problem – but for many other retrievals it is.

A second example of a geometry-dependent surface LER database is the geometry-dependent effective Lambertian-equivalent reflectivity (GE_LER) database introduced in a recent paper by Loyola et al. [2020]. The GE_LER approach does not depend on external data such as MODIS BRDF and uses machine learning techniques to retrieve the surface reflectivity from level-1 data of the sensor (GOME-2, TROPOMI, or another UVN sensor). Like the GLER, the GE_LER provides daily maps of the surface properties. Unlike the GLER, the GE_LER provides information for all surface types (land, ocean, snow/ice) and covers the UV-VIS-NIR spectral region.

In this paper we introduce the directionally dependent Lambertian-equivalent reflectivity (DLER) of the Earth's surface derived from GOME-2 observations. The surface DLER is retrieved as a function of the viewing geometry and therefore describes the anisotropy of the surface reflectivity. The DLER approach is very different than the GLER approach in that we perform a retrieval directly on GOME-2 level-1 data, not relying on BRDF input (or any other input) from an external database. In this way the wavelength bands, 26 in total, can be chosen freely, allowing the resulting DLER database to support the retrieval of most atmospheric species. A difference compared to the GLER and GE_LER databases is that the directional dependence of the DLER is provided as a parameterisation of the viewing angle. It is not mapped on a satellite footprint and serves as a climatological dependence. The directional approach of the GOME-2 surface DLER is therefore applicable to all polar satellites with equator crossing times close to that of GOME-2 (09:30 LT). This includes satellite instruments like GOME and SCIAMACHY, GOME-2 itself, and the future Sentinel-5/UVNS instrument scheduled for launch in 2023.

Like the GLER and GE_LER, the DLER is a Lambertian property and therefore can be used in situations where radiative transfer calculations include Lambertian surface reflection. … "

*P9 L11 The spatial resolution has changed to 40 km *40 km for GOME-2A. How large is the influence of combining measurements from two instruments with different spatial resolution? Is the instrumental degradation an issue in the DLER retrieval?*

GOME-2A data from 2013 and later years are not taken into account. There would have been quite an impact on the database if these data would have been taken into account. Not so much by the change in spatial resolution, but much more because of the reduction in the orbit swath (from 1920 km to 960 km). The change in orbit swath would have affected the traditional, non-directional LER retrieval mostly, because it is impacted directly by the change in the range of viewing geometries.

Because of the importance of consistency, we have decided not to include GOME-2A data from 2013 and later years. Another reason for not including the data is the lower quality of GOME-2A data from the later years. Also, the GOME-2A orbit has been drifting since June 2017.

Instrument degradation is an important issue that needs to be addressed properly. We correct for instrument degradation in the manner mentioned in [Tilstra et al., 2017] and described more extensively in [Tilstra et al., 2012]. Without a proper degradation correction the retrieved surface LER/DLER would be unusable for at least the shorter (UV) wavelength range.

To clarify the use of GOME-2A data in the database, we added the following sentence to item 4 in section 5 of the manuscript:

" Data from MetOp-A were used only until 2013, because in July 2013 the GOME-2A orbit swath was reduced from the standard 1920 km to 960 km. The reduction of the viewing angle range would have impacted the non-directional LER since it would then have been biased towards the LER values of the inner part of the orbit swath. ”

P12 L31 What is the reason of applying Eq 9 at 758 nm? P12 L29 concludes that 758 nm can be treated monochromatically.

Yes, the 758-nm wavelength band could well have been treated monochromatically. We decided to go further for the 758-nm and 772-nm wavelength bands because of their importance to cloud and aerosol retrieval using the O_2-A band. A strong argument for doing the additional work is that the absorption is caused by oxygen, not by water vapour. Because the amount of oxygen in the atmosphere is well known, the (very) small adjustment by taking absorption into account is very reliable and worth the additional effort.

To explain this we have added the following sentence to the manuscript:

“ For the 758 and 772-nm wavelength bands a monochromatic calculation would have sufficed, but because of their strong importance to cloud and aerosol retrieval using the O_2-A band we decided to go further than necessary by adopting spectral calculations. ”

P14 L26 Maybe it is good to show surface albedo maps here?

We agree and have now added maps of the surface LER to Figure 6. These are shown in Figure 1 of this AC.

References:

Gao, F., Schaaf, C. B., Strahler, A. H., Roesch, A., Lucht, W., and Dickinson, R.: MODIS bidirectional reflectance distribution function and albedo Climate Modeling Grid products and the variability of albedo for major global vegetation types, J. Geophys. Res., 110, D01104, doi:10.1029/2004JD005190, 2005.

Liu, S., Valks, P., Pinardi, G., Xu, J., Argyrouli, A., Lutz, R., Tilstra, L. G., Huijnen, V., Hendrick, F., and Van Roozendael, M.: An improved air mass factor calculation for nitrogen dioxide measurements from the Global Ozone Monitoring Experiment-2 (GOME-2), Atmos. Meas. Tech., 13, 755–787, doi:10.5194/amt-13-755-2020, 2020.

Lorente, A., Boersma, K. F., Stammes, P., Tilstra, L. G., Richter, A., Yu, H., Kharbouche, S., and Muller, J.-P.: The importance of surface reflectance anisotropy for cloud and NO2 retrievals from GOME-2 and OMI, Atmos. Meas. Tech., 11, 4509–4529, doi:10.5194/amt-11-4509-2018, 2018.

Loyola, D. G., Xu, J., Heue, K.-P., and Zimmer, W.: Applying FP_ILM to the retrieval of geometry-dependent effective Lambertian equivalent reflectivity (GE_LER) daily maps from UVN satellite measurements, Atmos. Meas. Tech., 13, 985–999, doi:10.5194/amt-13-985-2020, 2020.

Qin, W., Fasnacht, Z., Haffner, D., Vasilkov, A., Joiner, J., Krotkov, N., Fisher, B., and Spurr, R.: A geometry-dependent surface Lambertian-equivalent reflectivity product for UV–Vis retrievals – Part 1: Evaluation over land surfaces using measurements from OMI at 466 nm, Atmos. Meas. Tech., 12, 3997–4017, doi:10.5194/amt-12-3997-2019, 2019.

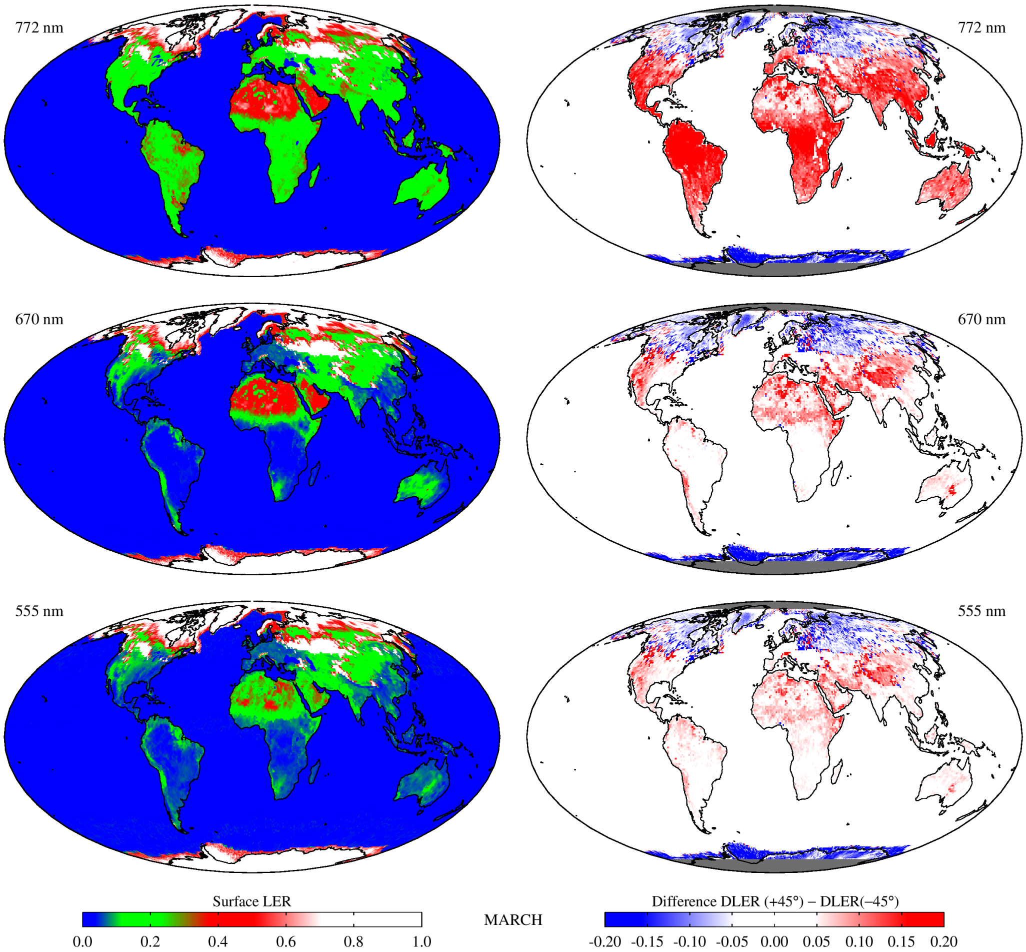

Figure 1: Left: Global maps of the GOME-2 surface LER, for calendar month March and for 772, 670, and 555 nm. Right: Global maps of the surface anisotropy parameter, defined as the difference between GOME-2 surface DLER at viewing angles of +45° and −45°. The surface anisotropy can be large, especially for vegetated surfaces at wavelengths beyond 700 nm. Over the oceans only non-directional surface LER is provided, as explained in Sect. 2.2.

Tilstra, L. G., de Graaf, M., Aben, I., and Stammes, P.: In-flight degradation correction of SCIAMACHY UV reflectances and Absorbing Aerosol Index, J. Geophys. Res., 117, D06209, doi:10.1029/2011JD016957, 2012.

Tilstra, L. G., Tuinder, O. N. E., Wang, P., and Stammes, P.: Surface reflectivity climatologies from UV to NIR determined from Earth observations by GOME-2 and SCIAMACHY, J. Geophys. Res.-Atmos., 122, 4084–4111, doi:10.1002/2016JD025940, 2017.

Vasilkov, A., Qin, W., Krotkov, N., Lamsal, L., Spurr, R., Haffner, D., Joiner, J., Yang, E.-S., and Marchenko, S.: Accounting for the effects of surface BRDF on satellite cloud and trace-gas retrievals: a new approach based on geometry-dependent Lambertian equivalent reflectivity applied to OMI algorithms, Atmos. Meas. Tech., 10, 333–349, doi:10.5194/amt-10-333-2017, 2017.