

## ***Interactive comment on “SO<sub>2</sub> Layer Height retrieval from Sentinel-5 Precursor/TROPOMI using FP\_ILM” by Pascal Hedelt et al.***

**Pascal Hedelt et al.**

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Received and published: 3 June 2019

First of all, many thanks for the detailed feedback and issues found. We provide feedback to each comment in the following:

- In this paper the authors present an algorithm to retrieve the altitude (or layer height, LH) of volcanic sulfur dioxide (SO<sub>2</sub>) clouds in near real-time using ultraviolet (UV) satellite data from the Sentinel-5P/TROPOMI instrument. TROPOMI provides the highest spatial resolution UV observations currently available from space. The injection altitude of SO<sub>2</sub> during volcanic activity is the main factor determining the climate impact of volcanic eruptions, and can also be used as a reasonable proxy for volcanic ash cloud altitude, which is required for aviation hazard mitigation. Hence accurate

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retrievals of SO<sub>2</sub> altitude are important and of broad interest to the atmospheric and volcano science community. The main advance described in the paper is the adaptation of an existing ‘machine learning’ SO<sub>2</sub> altitude retrieval algorithm (FP\_ILM) to the relatively new TROPOMI instrument. The advantage of the FP\_ILM algorithm over most existing SO<sub>2</sub> altitude retrievals is the fast processing speed, which allows it to run in near real-time.

- Overall I think the paper could be suitable for publication in AMT after some moderate revisions. The structure of the paper could be improved – currently there are many short paragraphs and not all the information is presented in a logical order, and many figures could be improved (see detailed comments below).

→ We will improve both text and figures

- I do question why the authors only simulated SO<sub>2</sub> layer heights up to a maximum of 20 km? Major volcanic eruptions (with the largest potential climate impacts) can inject SO<sub>2</sub> to greater altitudes and hence it would be interesting to see how the FP\_ILM algorithm would perform in such a scenario, given that the FP\_ILM retrievals of SO<sub>2</sub> at 20 km altitude appear least accurate for low SO<sub>2</sub> VCDs (e.g., Figure 4 suggests that a VCD > 40 DU is needed for accurate retrieval).

→ We will extend our training dataset to include SO<sub>2</sub> LH up to 30km. We will also show how the NN responds to SO<sub>2</sub> LHs not used in the training dataset.

- On a related note, under very high SO<sub>2</sub> loadings in a major eruption the ozone (O<sub>3</sub>) VCD retrievals may be inaccurate (due to SO<sub>2</sub> interference), and I assume this would preclude accurate SO<sub>2</sub> LH retrieval (since the O<sub>3</sub> VCD is a required input).

→ Small errors are expected in O<sub>3</sub> VCD and therefore the impact on the SO<sub>2</sub> LH retrieval should be minor. See Lerot et al (2013, “Homogenized total ozone data records from the European sensors GOME/ERS-2, SCIAMACHY/Envisat, and GOME-2/MetOp-A”): “The effect is negligible, except for a major volcanic eruption scenario

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with SO<sub>2</sub> column amounts exceeding 50 DU. In this case, total ozone errors may reach a few percent.” -We will show the influence of an inaccurate O<sub>3</sub> VCD on the retrieved SO<sub>2</sub> LH

- I also find that the stated SO<sub>2</sub> LH accuracy of ‘better than 2 km for SO<sub>2</sub> VCD > 20 DU’ is a little exaggerated, especially for higher SO<sub>2</sub> LH, e.g., for an SO<sub>2</sub> VCD of 20 DU at 20 km, the SO<sub>2</sub> LH appears underestimated by  $\approx$  5 km in Figure 3.

→We will update the figure, clearly showing the anticipated accuracy of 2km

→Furthermore we will compare our results to IASI and MLS results by determining the LH at the same overpass time using an dispersion model (i.e. HySplit)

- Another weakness is the validation of the TROPOMI SO<sub>2</sub> LH using IASI. Since IASI measurements are not coincident with TROPOMI, only broad conclusions can be drawn from the comparisons. In addition to CALIOP, the authors could explore the use of Microwave Limb Sounder (MLS) SO<sub>2</sub> data from the Aura satellite to validate the SO<sub>2</sub> LH retrievals.

→Good point. We will check whether we find MLS measurements for the volcanic cases studied. Unfortunately, IASI is the only other satellite source which we can use for the validation. In order to correct for the overpass time difference between S5P & IASI, we will use a trajectory model (HySplit) to forecast the IASI LH at the S5P overpass time

- P1, L21: there are many different ‘flavours’ of DOAS algorithm, so writing ‘the DOAS algorithm’ seems to be a major generalization. Furthermore, there should probably also be a reference to the first multi-spectral Total Ozone Mapping Spectrometer (TOMS) SO<sub>2</sub> retrievals, which used a different approach.

→We will update the text accordingly and add a reference to TOMS and other SO<sub>2</sub> retrievals (e.g. OMI PCA)

- P2, L1: ‘fast enough for NRT retrievals’ – algorithm speed/computational cost and the

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timeliness of retrievals are mentioned several times in the paper (e.g., P2, L19-20;P3, L3-5; P3, L17), but there is little quantitative information (I see that there is some information on P6). I would recommend adding a brief discussion to the introduction describing the data latency desired (e.g., for aviation safety and other applications) and estimates of current processing speeds.

→Very good point. The TROPOMI/S5P NRT data is available 3 hours after sensing. We will add a sentence describing the current processing speed of the operational SO2 VCD retrieval along with an estimation of the extra time needed for the SO2 LH retrieval

- P2, L2-4: I think any SO2 algorithm (regardless of whether an AMF is explicitly used) needs to make some assumptions regarding the SO2 vertical distribution (due to the pressure/ temperature dependence of SO2 absorption).

→Indeed, we will rephrase the sentence

- P2, L5: accurate AMF calculations could also include parameters such as cloud fraction, surface pressure and surface reflectivity. Also, it is not unique to the 305-335 nm range.

→Indeed, we will rephrase the sentence

- P2, L6: some of paragraph 2 basically restates the previous paragraph; i.e., the SO2 VCD is strongly dependent on the vertical distribution of SO2, as the latter strongly affects the AMF. These paragraphs could be reorganized/combined to clarify the text.

→We will reorganize the text

- P2, L10: it could be added here (instead of L16) that the usual approach for operational SO2 retrievals (not only from TROPOMI but also other UV sensors) is to assume several different a-priori SO2 vertical distributions and provide VCDs for each. I think it is also important to stress that above 5 km or so (i.e., in the upper troposphere and above), the vertical SO2 distribution has relatively little impact on the VCD (although the actual altitude is still of interest of course).

→We will update the text accordingly

- P2, L14: it is not only the number of photons but also the UV wavelengths interacting with the SO<sub>2</sub> layer that are influenced by the SO<sub>2</sub> layer height.

→Correct. We will update the text accordingly

- P2, L16: TROPOMI is first mentioned here, but some key information is provided later on L29 – some reorganization is needed.

→We will reorganize the paper to improve readability

- P2, L21: Extensive -> Extended.

→We will update the text accordingly

- P2, L22: it is not clear what is meant by 'strong volcanic eruptions'. Eruptions can be relatively weak and still produce high SO<sub>2</sub> column amounts, and vice versa.

→We will use the term Volcanic Explosivity Index (VEI) instead to clarify what is meant here

- P2, L26-27: is there a reference to support the statement that IR SO<sub>2</sub> height retrievals are more accurate than UV retrievals? I'm not sure that either approach has been extensively validated.

→The paper of Clarisse et al. (2014, see <https://www.atmos-chem-phys.net/14/3095/2014/>) on the Nabro eruption demonstrates that the IR is capable of being very accurate and sensitive to SO<sub>2</sub> height when the SO<sub>2</sub> columns are low. This paper also presents quite comprehensive validation with CALIPSO. Another (but similar) algorithm by the Carboni et al. (2016, see <https://www.atmos-chem-phys.net/16/4343/2016/>) shows equally good results. We will add these two references to our text

- P3, L3: It would be useful to know how often the algorithm needs to be 'trained'. Is

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re-training necessary if the TROPOMI data quality changes, or for other reasons?

→The algorithm needs to be re-trained only when large changes in the instrument slit function (ISRF) or SNR occur. Based on the experience from previous UV satellite sensors, large ISRF changes are not expected and, as can be seen from Figure 4, a (moderate) change in the SNR has no big impact on the SO<sub>2</sub> LH retrieval results.

- P3, L6: please also cite the first paper on the FP\_ILM SO<sub>2</sub> LH algorithm here. It might also be useful to briefly summarize the ‘improvements’ to the algorithm here too.

→We will add the reference here

- P3, L24: ‘plume profile’.

→We will update the text

- P4, L10: eight parameters were used to simulate the spectra, but a larger number (10) of PCs is needed to retrieve the layer height. This seems to contradict the authors assertion (P4, L9) that ‘fewer parameters’ are used to characterize the dataset after the PCA. Some more explanation/clarification may be needed here.

→The ‘fewer parameters’ refers to the comparison between 10 PCs and the corresponding 161 spectral points of the SO<sub>2</sub> LH fitting window.

- P4, L12: Figure 6 is the first Figure referenced here – in which case the Figures should be reordered.

→We will reorder the Figures accordingly.

- P4, L16: This paragraph (and also the following one) is probably difficult to follow for anyone not acquainted with neural networks or machine learning. Several new terms are introduced without elaboration (loss function, weight vectors, hidden layers).

→We will update the paragraph and add more information about NNs and machine learning

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- I recommend that the authors provide more details on the procedure.
  - We will update the text accordingly
- P5, L5: shouldn't the O3 VCD also be listed as a direct dependency?
  - That's correct, we will add it to the list
- P6, L2: from Figure 4, it appears that the accuracy of SO<sub>2</sub> LH retrieval does not significantly improve with increasing SNR for high altitude SO<sub>2</sub> LH (20 km). Can the authors explain this?
  - The SO<sub>2</sub> LH retrieval is more sensitive to higher-altitude plumes than to low-altitude plumes. Therefore, increasing SNR will improve the accuracy for low plumes but not so much for higher plumes.
- P6, L23: The IASI data are not the only source of independent SO<sub>2</sub> LH data. The Microwave Limb Sounder (MLS) on the NASA/Aura satellite can provide some information on SO<sub>2</sub> LH, albeit with limited spatial coverage and vertical resolution. The afternoon MLS overpass is nearly coincident with TROPOMI, and MLS did detect at least some of the eruptions discussed in the paper. I wonder if the authors considered using the MLS data to validate their SO<sub>2</sub> LH retrievals?
  - Good point. We will also include MLS results for Sinabung
- P6, L26: it would be useful to have at least a few more details on the Ambae volcanic activity (and actually for all the eruptions discussed in the paper), e.g., from the Smithsonian Institution Global Volcanism Program reports.
  - Ok, we will add more information on the volcanoes presented in this paper
- P6, L30: it is unclear why the plume is 'aged'? See general comment below regarding the SO<sub>2</sub> LH map (only pixels with robust LH retrievals should be shown). The two plumes discussed in the text are swamped by areas of blue (low SO<sub>2</sub> layer heights which I presume are incorrect due to the generally low SO<sub>2</sub> VCDs) and hence hard to

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see.

→With 'aged' we meant that the plume has already travelled from its source after the eruption until the S5P measurement took place. Actually we discovered that the image shows the plume with a time difference of 24 hours due to the date line: The plume in Fig.9 close to the volcano (around 180E) is the plume observed in the morning of 27 June, whereas the part of the plume around 150W is the same SO<sub>2</sub> cloud but observed on the evening of 27 June. We will hence update the figure accordingly. In the revised paper we will only show results for SO<sub>2</sub> close to 20DU.

- P7, L6: need to stress that this is also from Ambae.

→This sentence belongs to the Ambae section, so this should be clear. But we will make this more clear in the text

- P7, L8: acid rain is not usually an issue for stratospheric SO<sub>2</sub>.

→Indeed. We will correct the sentence

- P7, L15: a brief description and reference for the CALIOP instrument is needed (also provide the full name of the sensor).

→We will add a brief description for CALIOP

- P7, L16: it should be noted that it is not necessarily the case that SO<sub>2</sub> and ash/aerosols are collocated, as gas and ash can separate in volcanic clouds (e.g., as ash falls out to lower altitudes).

→Correct. We will point this out in the revised paper

Figures:

- Figures 3 and 4 are quite similar and could perhaps be combined as one figure.

→That's correct. We will combine the figures

- Figure 5: this figure is a bit cluttered and could perhaps be improved by removing



some of the data from the plot, e.g., using just the higher SO<sub>2</sub> VCDs.

→We will improve the figure

- Figures 7-15: General comment on the SO<sub>2</sub> map figures: I would recommend 'zooming in' as much as possible on the SO<sub>2</sub> plumes to show the detailed structure (especially Sinabung). Also, I think the SO<sub>2</sub> LH plots should only show those TROPOMI pixels with robust SO<sub>2</sub> LH retrievals (i.e., SO<sub>2</sub> VCD > 10-20 DU or so), since otherwise most of the plots are showing invalid data.

→We will make zoom-ins. The original intend was to show the same Lat-Lon range as when overplotting the IASI data.

- Figure 8: I'm not sure that it is necessary to show both the IASI-A and IASI-B SO<sub>2</sub> LH data. Since neither are coincident with TROPOMI, just show the overpass that is closest in time and/or which has the best coverage of the volcanic plume.

→Good point. Another idea would be to use the IASI data as input to a transport model (e.g. HySplit) and forecast the plume movement for the S5P overpass time to perform the comparison

- Figure 11: the CALIPSO satellite track corresponding to the lidar data in Figure 12 should be shown on the maps.

→We will add the ground track to the figure

- Figure 12: this figure is also not very clear. I recommend 'zooming in' to the volcanic plume to show the data more clearly, and only plotting the red symbols (SO<sub>2</sub> VCD > 20 DU). It is also not clear which features represent the Sinabung volcanic eruption cloud and which are meteorological clouds; this could be highlighted on the plot.

→We will update the plot and zoom-in to the volcanic plume

- Figure 13: the left-hand panel does not seem to show much if any useful IASI data. Given that there are CALIOP data for this case, perhaps the IASI data are not needed

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and this figure could be removed.

→Good point, we will remove the left panel

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Interactive comment on Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2019-13, 2019.

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