VOLCANIC SO2 NEAR-REAL TIME RETRIEVAL USING TROPOMI DATA AND NEURAL NETWORKS: THE DECEMBER 2018 ETNA TEST CASE

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ABSTRACT

During a volcanic eruption, large quantities of Sulphur dioxide (SO_2) are sometimes emitted into the atmosphere. Rapid detection and tracking of volcanic SO_2 clouds might be beneficial to air traffic security and to predict any correlated impact on the environment; for example, the possibility of acid rain events. Within the presented work, we exploited Sentinel-5p radiance data (Level 1b) to detect and retrieve SO_2 volcanic emissions through a neural network based algorithm that produces rapid SO_2 vertical column estimates. The dataset used for training the net was composed of 13 TROPOMI Level 2 "Offline" SO_2 data collected during the Etna Volcano eruption that occurred in 2018 from 22 December to 1 January. Experimental results are very encouraging and open to the perspective of make available a new and stable product for monitoring atmospheric SO_2 clouds on a global scale based on Sentinel-5p acquisitions.

Index Terms— Volcanic Clouds, Sulphur Dioxide, Sentinel-5p, TROPOMI, Neural Networks

1. INTRODUCTION

Sentinel-5p is the most recent addition, together with the latest Sentinel-6, to the family of Sentinel satellites monitoring the Earth and it is the first satellite dedicated to measuring atmospheric chemistry and greenhouse gases within the Copernicus program (more info about the Copernicus program available at https://www.copernicus.eu/). Sentinel-5p flies in a sun-synchronous polar orbit, at an altitude of 804 km and it is equipped with a brand new instrument called TROPOMI (TROPOspheric Monitoring Instrument), which is an optical sensor covering bands from the Ultraviolet (UV) to Near infrared (NIR) and Shortwave Infrared (SWIR). TROPOMI is an imaging spectrometer and it looks at the Earth, in a native spatial resolution of 3.5 x 7 km, identifying the constituents of the atmosphere and their concentration [1]. One of the analyzed substances is Sulphur dioxide (SO_2) and one of the Sentinel-5p mission objectives is to provide crucial information about volcanic SO_2 quantification and dispersion in the atmosphere in near real time.

From the raw data collected by Sentinel-5p, the retrieval of SO_2 vertical column of the TROPOMI standard products is based on the Differential Optical Absorption Spectroscopy (DOAS) technique and it is obtained with different processing modes depending on the releasing time.

Volcanoes are the main natural sources of pollution since they emit large quantities of solid particles (ash) and gases (e.g. H_2O, CO_2, SO_2) into the atmosphere. The strong interest in determining the abundances of these emissions and their spatial and temporal distribution is mainly due to the effect on health [2], the impact on the environment [3], climate [4] and its potential role as proxy for volcanic ash [5; 6].

When a volcano erupts, there is a strong need to have as much existing data available and in the shortest possible time for helping to monitor the state of the eruption and its emission of ash and gases into the atmosphere. Furthermore, accurate and rapid estimates about SO_2 vertical column abundance could be used in an assimilating model that predicts the evolution of the SO_2 cloud. Starting from these assumptions, the scope of our work was to obtain a new SO_2 product from Sentinel-5p data through a neural network (NN) based algorithm.

An approach based on neural networks, which is able to grasp even weak non-linear relationships between all the variables involved, can be a valuable solution in the case of inversion problems and estimation of atmospheric parameters. The effectiveness of neural networks for the estimation of atmospheric constituents has already been demonstrated in several studies (e.g. [7; 8]). In the context of volcanic emissions, NN based algorithms were developed and successfully tested for volcanic ash detection and retrieval with MODIS data in previous works [6; 9; 10].

2. METHODOLOGY

Our approach exploits the existing TROPOMI standard "offline" (OFFL) data to train a neural network able to obtain a new product useful for volcanic SO_2 detection and retrieval in near-real time.

The structure of the algorithm considers the relationship between the spectral radiance over certain wavelength ranges provided by the TROPOMI L1b product and the corresponding SO_2 total column concentration computed over the same geographical area.

Table 1: SO_2 absorption ranges and corresponding TROPOMI L1b bands

Standard product SO2 absorption windows	TROPOMI L1b Band 2 and Band 3 ranges
312 – 326 nm	Band 2 (300 – 320 nm)
325 – 335 nm	Band 3 (320 – 405 nm)
360 – 390 nm	

We considered as input the same absorption ranges used for the retrieval of the SO_2 abundance in the atmosphere reported in the standard TROPOMI "offline" vertical column SO_2 product. The absorption windows are reported in Table 1, together with the spectrum ranges covered by the photon radiance included in the TROPOMI Level 1b standard product.

In order to derive SO_2 vertical column abundance, a multi-layer perceptron (MLP) neural network was designed and trained adopting a sigmoid activation function for each layer, described by the following equation.

$$\boldsymbol{f(x) = \frac{1}{1 + e^{-x}}} \quad (1)$$

For taking into account the interferences occurring between the SO_2 absorption signature with the O_3 absorption spectrum, the neural network algorithm was developed considering also the total ozone column concentration among the targets. This approach can facilitate the NN in understanding the relationship between certain spectral radiance values and the corresponding SO_2 and O_3 total column abundance, considering the aforementioned three absorption range in the UV region.

Among the input, we considered also solar zenith angle (SZA), viewing zenith angle (VZA) and relative azimuth angle (RAA) that together give information about the geometry of acquisition, which affects the spectral radiance value for each pixel and, on the other hand, the resulting SO_2 vertical column density. The angles values were obtained from the same L1b TROPOMI products that contain the spectral radiances.

We used Python as development environment and Keras, a Tensorflow high-level API, for the implementation of algorithms based on artificial neural networks written in the Python language, for designing the MLP net.

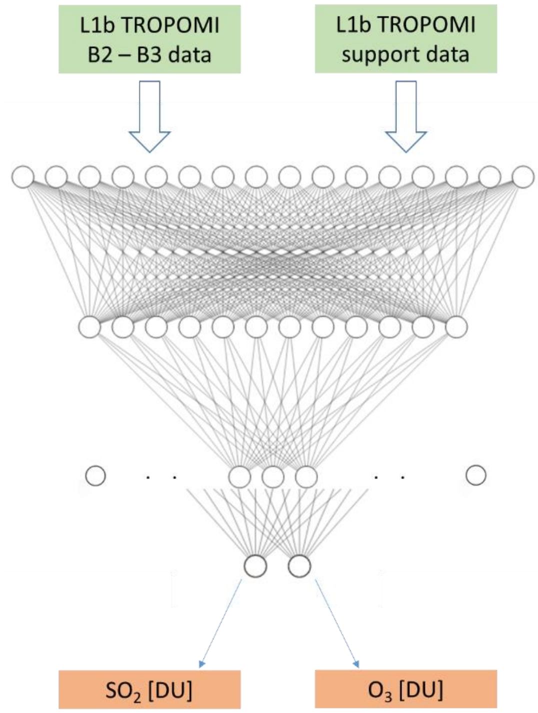

Figure 1: Neural network model tested for SO_2 retrieval.

All the data used for training the neural network were selected among the best quality data (qa value > 0.9) group included into the TROPOMI L1b and L2 support data, ensuring the best accuracy as possible for the training set and, consequently, for the algorithm performance.

The training dataset consisted of 13 Sentinel-5p data acquired between the 22 December 2018 and 1 January 2019 along the orbit passing over the Etna area, when an intense volcanic activity has been registered for some days.

Sentinel-5p TROPOMI data are freely and open accessible via https://s5phub.copernicus.eu/.

3. EXPERIMENTAL RESULTS AND DISCUSSION

We applied the trained neural network to the TROPOMI L1b image collected on Etna the 29 December 2018 at 11:23 UTC to obtain the SO_2 total columnar concentration in a day characterized by eruptive activity. Figure 2 shows the Sentinel-5p Level 2 "offline" SO_2 product and that obtained from the developed NN approach. The SO_2 total column density is expressed in Dobson Unit (DU).

The NN based estimates for SO_2 presented a general accord with the corresponding values reported in the TROPOMI L2 OFFL Standard product of the same date, which was assumed as ground truth. Even if the SO_2 column abundance reported in the NN based product is still affected by some underestimations, the preliminary results of our approach for the SO_2 detection and retrieval by means of neural network trained with TROPOMI L1b data were encouraging.

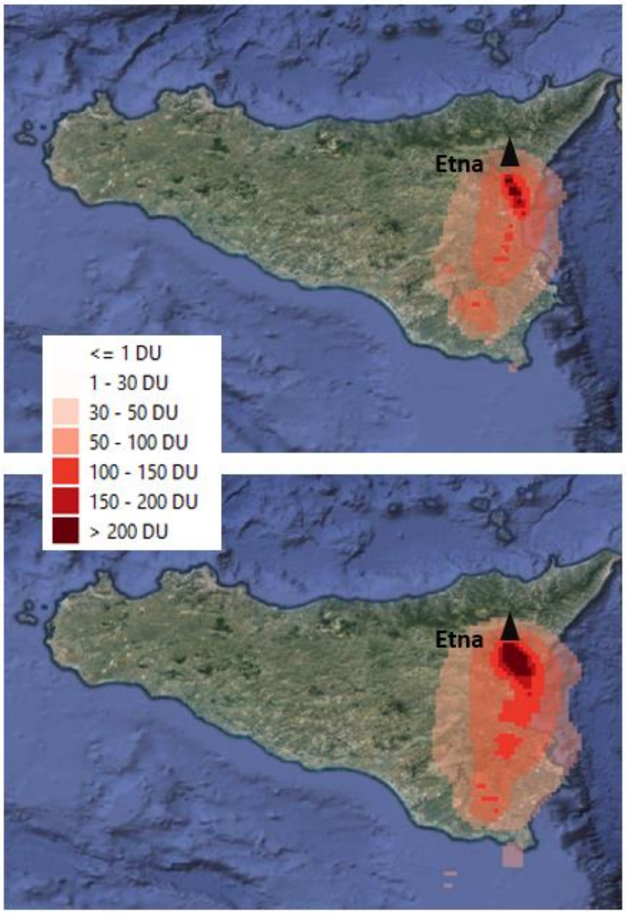

Figure 2: NN based SO_2 retrieval for the TROPOMI L1b data collected on Etna the 29 December 2018 at 11:23 UTC (above); SO_2 total column abundance reported in the TROPOMI L2 SO_2 "offline" product of the same date and freely available via https://s5phub.copernicus.eu/ (below).

The neural network predictions seem to identify the SO_2 value distribution of the TROPOMI standard product correctly, showing, in particular, the higher total column abundance over the same pixels. In order to quantify the algorithm accuracy, the Root Mean Squared Error (RMSE), Mean Absolute Error (MAE) and Pearson Coefficient (R) were computed; the corresponding values are reported in Table 2.

Our NN model performance can be assessed as positive looking at the standard deviation value (20.969 DU) of the data contained in the product assumed as ground truth, which is higher than the RMSE. Furthermore, the average value of SO_2 total column density of the NN based product is very close to that of the TROPOMI standard product (7.972 DU).

Table 2: Summary of the trained NN performance on the test case.

RMSE	MAE	R (Pearson)
13.081 DU	5.523 DU	0.792

4. CONCLUSIONS

We tested a new methodology for the fast retrieval of SO_2 total column concentration with Sentinel-5p TROPOMI data. A MLP neural network was designed and trained with a database containing 13 Sentinel-5p data acquired from 22 December 2018 to 1 January 2019, excluding the image collected on the 29 December 2018, which was used to test the trained NN model.

Experimental results were promising and shown that the neural network designed for this work was able to quantify the SO_2 total column abundance starting from the spectral radiance values recorded by TROPOMI. The neural network based SO_2 estimates were in a general agreement with the corresponding Sentinel-5p L2 "offline" product obtained through the DOAS technique.

In future development we will extend the training dataset, test the possible modification of NN architecture and also further fine-tuning of neural network's hyperparameters, in order to obtain a higher accuracy of the algorithm.

5. ACKNOWLEDGMENTS

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