SO₂ Plume Height Retrieval: Applying Inverse Learning Machines to MetOP/GOME-2 and S5p/TROPOMI

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Background

Precise knowledge of the location and height of the volcanic sulfur dioxide (SO₂) plume is essential for accurate determination of SO₂ emitted by volcanic eruptions. Current UV-based SO₂ plume height retrieval algorithms are very time-consuming and therefore not suitable for near-real-time applications. Here we present a novel method called the Full-Physics Inverse Learning Machine (FP-ILM) algorithm for extremely fast and accurate retrieval of the SO₂ plume height:

- Mapping between spectral radiance and SO₂ plume height using supervised learning methods.
- Combination of smart grid sampling, dimensionality reduction and a non-linear regression analysis scheme based on PCA and a neural network.
- Offline radiative transfer computations of a training dataset to determine inversion operator (FP-ILM) which is robust and computationally simple.

The main advantage of the FP-ILM over the classical optimization approach is that the time-consuming training phase involving complex RT modeling is performed offline; the inverse operator itself is robust and computationally simple.

During the training phase, an 8-dimensional training dataset of simulated reflectance spectra is computed using the full-physics forward radiative transfer model LIDORT-RSS (Spurr et al. 2008). Reflectance spectra are calculated in the wavelength range 310-335nm as a function of SO₂ VCD and plume height, surface albedo, surface height, O₃ VCD, and geometrical angles (SZA,VZA,RAA).

The next step of the FP-ILM consists of a training phase, and an operational phase. The FP-ILM used for estimating plume height values is a neural network trained using a Neural Network (Multilayer Perceptron Regression). Conceptually, the FP-ILM consists of a training phase, and an operational phase. Figure 1 shows a schematic representation of the FP-ILM used for estimating plume height values. The main advantage of the FP-ILM over the classical optimization approach is that the time-consuming training phase involving complex RT modeling is performed offline; the inverse operator itself is robust and computationally simple.

Offline radiative transfer computations of a training dataset to determine inversion operator (FP-ILM) algorithm for extremely fast and accurate retrieval of the SO₂ plume height is presented.

Application to GOME-2 data—Kasatochi (Aleutian Islands)

Mt. Kasatochi erupted on 7 August 2008 with three distinctive explosive eruptions. About 2 Mt of SO₂ were released into the stratosphere, together with large amounts of ash. The SO₂ plume was transported over the entire Northern hemisphere and was detectable by GOME-2 for several weeks. The plume height retrieval using the FP-ILM detects the SO₂ plume at an altitude in the range 9 to 10 km, with some parts of the plume even reaching altitudes of 15km in those parts of the plume with very high SO₂ amounts, see Efremenko D.S., Loyola D., Hedelt P., Spurr R. (2017).

Figure 3 shows the retrieved plume height (left panel) and the calculated VCDs (right panel) for the three days after the eruption, i.e. from 8 August (upper row) to 10 August (lower row). The results are in very good agreement with those obtained by Yang et al. (2010) using a direct fitting approach.

Application to TROPOMI data—Sinabung, Indonesia

Mt. Sinabung in Indonesia erupted on 19 February 2018 after a long period of inactivity, with a thick ash and gas plume causing the evacuation of more than 30,000 people. The FP-ILM plume height retrieval detects the SO₂ plume at an altitude in the range 11 to 18 km in the center of the plume, see Fig. 4.

On the same day, the CALIOP instrument aboard CALIPSO (NASA) had an overpass right above the plume, detecting debris and gas from the eruption in the range between 15 to 18km. The SO₂ plume height retrieved by IAS is in the range 14 to 18km (L. Clarisse, ULB, pers. comm.).

The left panel shows the retrieved plume heights, and the right panel shows the total SO₂ column density.

The error of the FP-ILM strongly depends on the signal-to-noise ratio (SNR) in the spectrum and on the values of the SO₂ total column. For SNRs larger than 500 the FP-ILM can capture the information related to the plume height, while for the SNRs less than 100 the correlation between the predicted and actual values of the plume height is low (the plume height information is hidden by noise). Also note that the sensitivity of the model decreases with the SO₂ total column.

Figure 2 shows the FP-ILM operator applied to an artificial test dataset with a SNR of 1000 including a range of viewing geometries, SO₂ total column and plume height levels.

Clearly visible is the underestimation of the plume height below about 20 DU. Above 20 DU, the difference between the real and the retrieved plume height is less than 2km, with a decreasing difference at higher SO₂ columns.

Accuracy analysis

The error analysis of the FP-ILM strongly depends on the signal-to-noise ratio (SNR) in the spectra and on the values of the SO₂ total column. For SNRs larger than 500 the FP-ILM can capture the information related to the plume height, while for the SNRs less than 100 the correlation between the predicted and actual values of the plume height is low (the plume height information is hidden by noise). Also note that the sensitivity of the model decreases with the SO₂ total column.

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Error analysis

The error analysis of the FP-ILM strongly depends on the signal-to-noise ratio (SNR) in the spectrum and on the values of the SO₂ total column. For SNRs larger than 500 the FP-ILM can capture the information related to the plume height, while for the SNRs less than 100 the correlation between the predicted and actual values of the plume height is low (the plume height information is hidden by noise). Also note that the sensitivity of the model decreases with the SO₂ total column.

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References


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