MONITORING OF VOLCANIC ERUPTIONS AND DETERMINATION OF SO_2 PLUME HEIGHT FROM GOME-2 MEASUREMENTS

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ABSTRACT

Satellite-based remote sensing measurements of atmospheric sulphur dioxide (SO_2) provide valuable information on anthropogenic pollution and volcanic activity. Sensors like GOME-2 on MetOp-A make it possible to monitor SO_2 emissions on a global scale and daily basis. SO_2 total column amounts are retrieved in near-real time using the UV range of backscattered sunlight making it possible to detect and track volcanic eruption plumes as a valuable tool for aviation warning. For aviation safety the correct determination of the plume height is a central issue. Therefore a novel method has been developed for the determination of the plume height in near-real time based on the operational DOAS retrieval combined with an iterative look-up table (LUT) approach. The method has been applied to the eruption of Eyjafjöll volcano, April - May 2010, and to the eruption of Kilauea, July 2008.

1. INTRODUCTION

Atmospheric sulphur dioxide is produced mainly by volcanic eruptions and anthropogenic activities like power plants, metal smelting, refineries and burning of fossil fuels. Due to its generally low background level it is an excellent marker for pollution events and volcanic activity. Its lifetime varies from approximately 1-2 days in the troposphere to several weeks in the stratosphere. In the troposphere it is transformed into sulfuric acid and is responsible for acid rain. If SO_2 is brought into the stratosphere by volcanic eruptions, it can remain there for several weeks and travel over long distances (e.g. Kasatochi eruption, Aug. 2008), as sulfuric aerosols it can also have a cooling effect on the atmosphere.

Volcanic eruptions pose a major danger to people living in the vicinity of volcanoes. With the fast growing population more and more people live close to active volcanoes. Besides being a direct danger to the local population, volcanic eruptions have also proven to be a major hazard to aviation. A central issue for aviation safety is the determination of the SO_2 plume height to avoid flying through volcanic plumes. As the injection height also determines the further distribution of the volcanic cloud, it is an important input parameter for modelling and forecasting the future development of the plume. The altitude of the volcanic SO_2 also plays an important role in determining the climatic effects of an eruption, as sulphate aerosols forming from SO_2 can persist in the stratosphere for a long time and lower the global surface temperature (Pinatubo eruption, 1991) [1].

Satellite-based instruments operating in the ultraviolet (UV) spectral region have played an important role in monitoring and quantifying SO_2 emissions. The Total Ozone Mapping Spectrometer (TOMS) was the first satellite instrument to detect volcanic SO_2 released during the El Chichon eruption in 1982 [2]. The detection sensitivity for SO_2 was limited to large SO_2 amounts due to the discrete wavelengths that were designed for ozone measurements. The detection limit for SO2 greatly improved for the Global Ozone Monitoring Experiment (GOME) launched 1995 onboard the ERS-2 satellite and the Scanning Imaging Spectrometer for Atmospheric Cartography (SCIAMACHY) launched in 2002 onboard the ENVISAT satellite. However, these instruments have a fairly poor spatial coverage. They need several days for the acquisition of a contiguous global map and may therefore miss smaller short-lived volcanic events. The newest UV satellite sensors OMI (Ozone Monitoring Instrument) on EOS-Aura since 2004 and GOME-2 on MetOp-A [3] since 2006 make it possible to monitor volcanic activity and anthropogenic SO_2 pollution on a global scale and daily basis.

Recently several techniques have been developed to retrieve the volcanic plume height from satellite observations. One is the inverse trajectory modeling that uses a trajectory model to simulate the SO_2 transport for several assumed injection heights and matches the results with satellite observations to determine the most probable plume height [4]. A second approach is based on an extension of the Iterative Spectral Fitting (ISF)

Proc. 'ESA Living Planet Symposium', Bergen, Norway
28 June – 2 July 2010 (ESA SP-686, December 2010)

algorithm for the OMI instrument and can retrieve ozone column, SO_2 column and SO_2 altitude simultaneously [5]. Both techniques have proven their ability to determine volcanic eruption heights, however, these techniques are computationally quite time consuming. Therefore a new approach has been developed to estimate the plume height in NRT using the results of the operational DOAS fit combined with an iterative LUT approach.

2. RETRIEVAL OF SULFUR DIOXIDE

Total SO_2 columns are retrieved from measurements of the GOME-2 instrument on MetOp-A. GOME-2 is a nadir-scanning UV-VIS spectrometer with a spectral coverage of 240 – 790 nm and a spectral (FWHM) resolution between 0.26 nm and 0.51 nm. It measures the back-scattered radiation from the earth-atmosphere system. In addition, a direct sun spectrum is recorded once a day. The nominal size of the field of view is 80 km x 40 km. With the normal operation mode near global coverage is achieved at the equator in one day. The operational GOME-2 total column SO_2 product is produced by the German Aerospace Center (DLR) in the framework of EUMETSAT’s Satellite Application Facility on Ozone and Atmospheric Chemistry Monitoring (O3M-SAF), the PROMOTE and the Exupéry projects.

SO_2 columns are retrieved from GOME-2 UV backscatter measurements of sunlight in a two-step procedure [6]. In a first step, slant column densities (SC) of SO_2 are determined using the well established Differential Optical Absorption Spectroscopy (DOAS) method [7] in the wavelength region between 315 – 326 nm. Input parameters for the DOAS fit include the absorption cross-section of SO_2, for which the temperature is adjusted depending on the assumed height of the volcanic SO_2 plume, and the absorption cross-sections of interfering gases, ozone and NO_2. A further correction is made in the DOAS fit to account for the ring effect (rotational Raman scattering).

In the 315 – 326 nm wavelength range used for the retrieval a strong interference of the SO_2 and ozone absorption signals can be observed, especially at high solar zenith angles. Therefore, an interference correction needs to be applied to the SO_2 slant column values [6].

In a second step, the corrected slant column densities of SO_2 are converted to geometry-independent vertical column (VC) amounts through division by an appropriate air mass factor (AMF) as VC = SC/AMF.

For SO_2, the AMF is strongly dependent on measurement geometry, surface albedo, clouds, aerosols, and most importantly, the shape of the vertical SO_2 profile in the atmosphere. For the AMF calculations, an a priori volcanic SO_2 profile is assumed with a predefined central plume height. As the correct plume height is rarely available at the time of measurement, the SO_2 column is computed for three different assumed volcanic plume heights: 2.5 km, 6 km and 15 km above ground level. The lowest height represents passive degassing of low volcanoes, the second height effusive volcanic eruptions or passive degassing of high volcanoes and the third height explosive eruptions. The AMFs are calculated with the radiative transfer model LIDORT [8].

3. PLUME HEIGHT ESTIMATION IN NEAR-REAL TIME

When using backscattered radiation to determine the SO_2 column amount the altitude of the SO_2 layer in the atmosphere plays an important role as it determines the proportion of photons that pass the absorbing layer on their way to the sensor. The higher the layer altitude the more photons are Rayleigh scattered below and therefore pass through the SO_2 layer resulting in more prominent SO_2 absorption structures in the measured radiances. If the layer is low in the atmosphere more photons are scattered above. Therefore the measured radiances also contain information about the SO_2 plume altitude. Using the SO_2 column amount retrieved with the operational DOAS approach the height of the plume can be estimated by matching the measured radiances with simulations performed for different plume heights.

The simulated radiances are computed with the Raman scattering version of the radiative transfer model LIDORT [9]. Input parameters include SO_2 column, ozone column, viewing geometry, surface albedo, cloud fraction and cloud top albedo. The input parameters are taken from the operational GOME-2 product at DLR. For the SO_2 column the retrieval result for an assumed plume height of 15 km is used as first guess. Using these input parameters backscatter radiances are simulated for different assumed plume heights, which are currently 2 km, 5 km, 7 km, 9 km, 11 km, 13 km and 15 km. For modeling a Gaussian SO_2 profile is used and plume heights given refer to the central heights of these profiles. For the simulations a wavelength range between 310 nm – 320 nm is used. The simulated spectra are then matched with the measurement and the one with the smallest residual, that is the one that shows the smallest difference to the measured spectrum, is selected as the most likely plume height. If this plume height is not equal to the plume height assumed for the DOAS retrieval in the first step, the retrieval is redone with the new plume height and the whole process is repeated. This is iterated until assumed and retrieved plume height converge.

First tests have shown that the retrieval works well for intermediate SO_2 column amounts. For very low SO_2

values (< 2 DU), the differences between the simulated radiances are not large enough to provide a reasonable result, as uncertainties in other input parameters have stronger effects than changes in the assumed plume height. Further issues arise for large SO_2 columns (> 60 DU). In this case the DOAS approach underestimates the total SO_2 amount, as the assumption of an optically thin atmosphere is not valid. This affects the height retrieval as the SO_2 amount assumed for the simulations is far too low.

First results using a direct fitting approach show that this underestimation of SO_2 total columns can be very strong, e.g. for the eruption of Kasatochi volcano, August 2008, maximum values retrieved with a direct fitting approach are about three to four times higher than those retrieved with the standard DOAS method (Fig. 1).

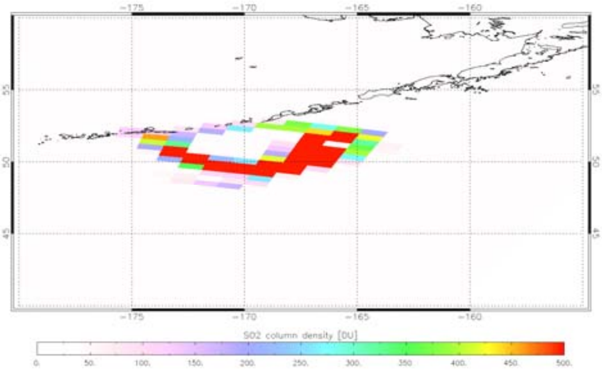

Figure 1: *SO_2 total columns from the Kasatochi eruption, August 2008, retrieved with a direct fitting approach. Maximum values detected are up to ~500 DU compared to ~120 DU detected with DOAS retrieval.*

The major advantage of this height estimation is that the computationally demanding part, simulating the spectra, can be done beforehand. These spectra are stored in a look-up table (LUT). In case of a volcanic eruption the plume height can be estimated within minutes after the operational retrieval of the total column and provide timely information for aviation safety issues.

4. CASE STUDIES

The new approach to determine the SO_2 plume altitude has been tested on several volcanic eruptions. One example for an explosive volcanic eruption reaching medium atmospheric altitudes is the Eyjafjöll eruption in Iceland. The second case is Hawaii as an example of a lower effusive eruption.

4.1. Eyjafjöll, Iceland

Starting on 14 April and lasting until 23 May 2010 the explosive eruption of Eyjafjöll volcano in southern Iceland caused widespread disruption to aviation in large parts of Europe. The closure of the European airspace for several days caused unprecedented difficulties, enormous economic losses and left thousands of passengers stranded at airports throughout Europe. Explosive activity started on 14 April 2010, the first phase of the eruption produced an ash rich plume of 5-9 km altitude and lasted until 17 April. The prevailing winds carried the ash to the southeast and south towards Europe which resulted in the closure of large parts of the European airspace. After that the activity dropped until 4 May, when explosive activity picked up again, producing ash columns of up to 9 km height, which again resulted in partial closure of the European airspace. The activity of Eyjafjöll volcano ended 23 May.

As SO_2 emissions were relatively low during the first phase of the eruption, with total column values rarely exceeding the threshold of 2 DU necessary for height estimation, a day in the second eruption phase was selected as a test case. During this second eruption period the SO_2 emissions were considerably higher (Fig. 2, left) but with values of up to 10 DU they still well below the amounts where the DOAS fit causes problems. Therefore one day from this period was chosen to test the new height estimation method. For 5 May all GOME-2 pixels with SO_2 total column amounts over 2 DU were selected and radiances were simulated for different assumed plume heights. Most resulting heights vary from 7 – 11 km (Fig. 2, right) and match

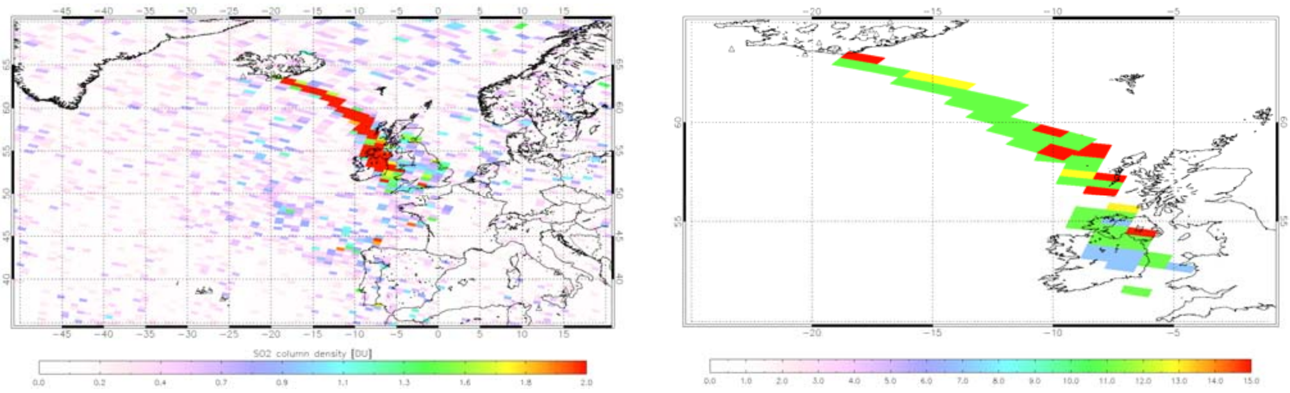

Figure 2: *Volcanic SO_2 plume from Eyjafjöll eruption (left) and estimated plume height (right) on 05 May 2010*

very well with reported plume heights of around 9 km for that day. Only one to two iterations were necessary for the convergence of the height retrieval. Keeping in mind that the reported plume height refers to the height of the ash plume and the SO_2 might be at different altitudes, a simulation using the FLEXPART model [10] was used for comparison. It shows plume heights of 6 – 14 km for 5 May, so the retrieved height is well within the possible height range. There are however several pixels showing heights of 15 km which seems definitely too high for that day. A possible reason is the simplified treatment of clouds which are currently only considered by a change in albedo, but further investigation is needed.

4.2. Kilauea, Hawaii

An example for a different type of eruption is the effusive emission of lava and gas at Kilauea volcano on Hawaii. Kilauea volcano has been Hawaii's most active volcano in historical times. The current eruptive episode began in 1983 and is still ongoing. Lava flows from this eruptive episode have covered more than 100 km², destroyed houses and roads and added to the coastline of the island [11].

As an example for the SO_2 plume height retrieval the 9 July 2008 was selected, as a day with fairly high SO_2 emissions including several pixels containing SO_2 column amounts > 2 DU (Fig. 3). Comparison of simulated and measured radiances resulted in estimated heights of ~ 5 km (Fig. 4, left) 2 - 3 iterations of DOAS retrieval and height determination were necessary to estimate the final plume height, which shows that also for heights that are quite different from the originally assumed 15 km the height estimation converges quite rapidly. Trajectory modeling for that day shows that the SO_2 has been lifted by atmospheric winds to heights of 3 - 4 km (Fig. 4, right) which is very close to the estimated SO_2 height.

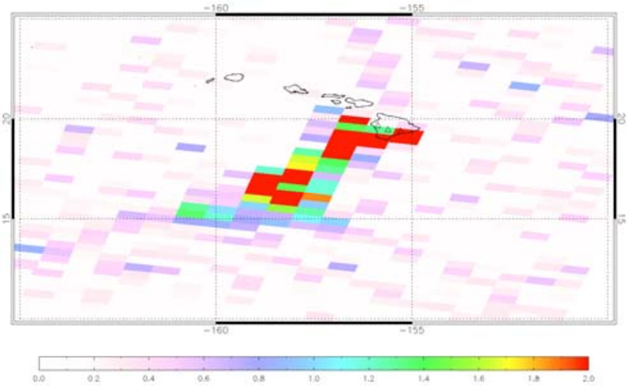

Figure 3: *Volcanic SO_2 emissions from Kilauea volcano, 09 July 2008*

5. CONCLUDING REMARKS

Sulfur dioxide monitoring from satellite instruments has proven to be a valuable tool in monitoring volcanic activity and reducing the hazards related to it. Recently several methods have been developed to retrieve the SO_2 plume altitude from satellite observations, as this information is extremely important for aviation safety. A novel method that allows the timely retrieval of SO_2 plume altitudes from GOME-2 observations has been developed. Using a set of pre-calculated radiances for various conditions and plume heights, an estimation of the plume height is achieved in an iterative process by matching the measured radiances with the simulated ones that best represent the atmospheric conditions taken from the operational SO_2 and O3 retrieval.

First tests on volcanic events have shown promising results. The results of the plume height estimation seem reasonable and the retrieval can clearly distinguish between the higher plume altitudes of the Eyjafjöll eruption and the lower altitudes from the effusive

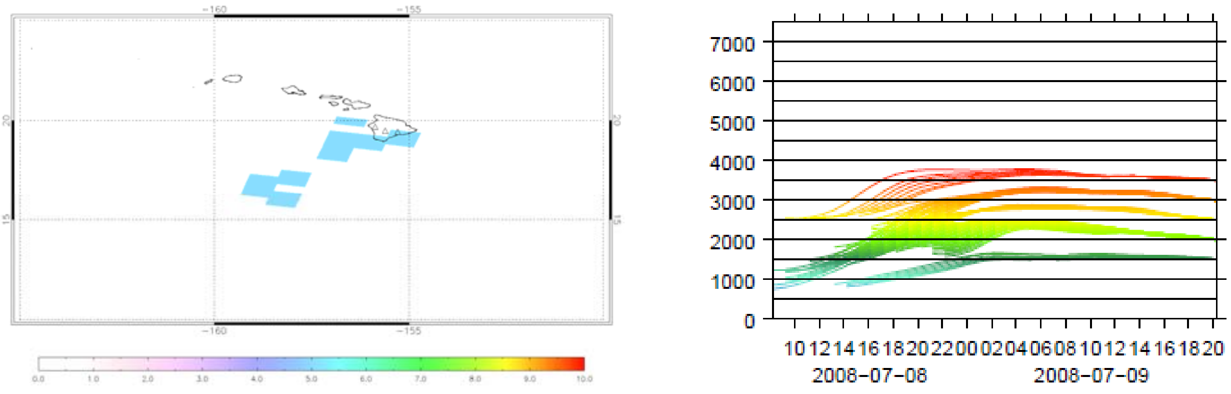

Figure 4: *SO_2 plume height estimation for Kilauea volcano, 09 July 2008, using the new LUT approach (left) and a trajectory model (right). Both methods show similar results.*

eruption of Hawaii. Estimated SO_2 altitudes are within ~ 2 km of the results derived using trajectory modeling. The retrieval converges towards one height fast, normally within 2 - 3 iterations. With first estimates showing accuracies of 1 - 2 km this altitude retrieval is not as accurate as for example the ISF algorithm with accuracies of up to ~ 0.1 km [5] but the main advantage is the possibility to deliver a first reasonable estimate of the SO_2 plume altitude in NRT.

Further tests are needed to determine the accuracy of the altitude estimation. The sensitivity of the height estimation to different input parameters included in the retrieval has to be tested in more detail to decide if any parameters, e.g. clouds, have to be treated in a more sophisticated way and to set up the final LUT. Overall initial results look promising and the method has shown the potential to deliver a first estimate of the plume altitude on a NRT basis.

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ACKNOWLEDGEMENTS

The research described in this paper has been performed within Exupéry, developed within the German GEOTECHNOLOGIEN Program, the ESA/DUE project GlobVolcano and the Aviation Control Support service of the GMES Service Element for Atmospheric Monitoring (PROMOTE). The GOME-2 level-1 data were provided by EUMETSAT.

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