SO_2 column and plume height retrieval from direct fitting of GOME-2 backscattered radiance measurements

Introduction

The use of satellite measurements for SO_2 monitoring has become an important aspect in the support of aviation control. Satellite measurements are sometimes the only information available on SO_2 concentrations from volcanic eruption events and enhanced SO_2 may indicate the presence of ash. Satellite instruments also provide information on SO_2 pollutions sources. SO_2 columns have been derived from several UV nadir sensors (GOME, SCIAMACHY, GOME-2) with traditional DOAS methods. However, both SO_2 and O_3 strongly absorb in the UV range of 310-320 nm (Figure 1); this limits the accuracy of the DOAS technique, which is valid for optically thin media only. **We therefore present an enhanced technique for the simultaneous retrieval of total vertical columns of O_3 and SO_2 from satellite measurements**. The method involves direct fitting of simulated Earthshine radiances to the measured radiance spectrum. **In the process, the use of parameterized vertical SO_2 profiles allows for the derivation of the peak height of the SO_2 plume, along with the total column amounts.**

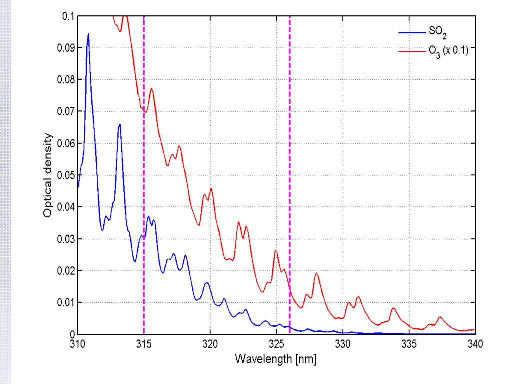

Figure 1 *UV absorption spectrum of O_3 and SO_2. Note the scaling of the ozone spectrum. The dashed lines indicate the retrieval fitting window mostly used when retrieving SO_2 from GOME or SCIAMACHY data. We have also adopted this window for our current study.*

Background physics

The way different layers of the atmosphere contribute to the top-of atmosphere radiance spectrum I_{TOA}, can be visualized by means of the vertical profile of the local air mass factor and its gradient (Figure 2). The respective quantities are major components of the I_{TOA} Jacobians with respect to total gas column and gas height. Yang *et al*. [2010, [3]] showed and explained the differences between these two weighting functions. Put in words: **Changing the SO_2 concentration in an atmospheric layer has a different effect on I_{TOA} than changing the altitude of this layer.** This phenomenon allows for the derivation of both total column and height information of an SO_2 plume.

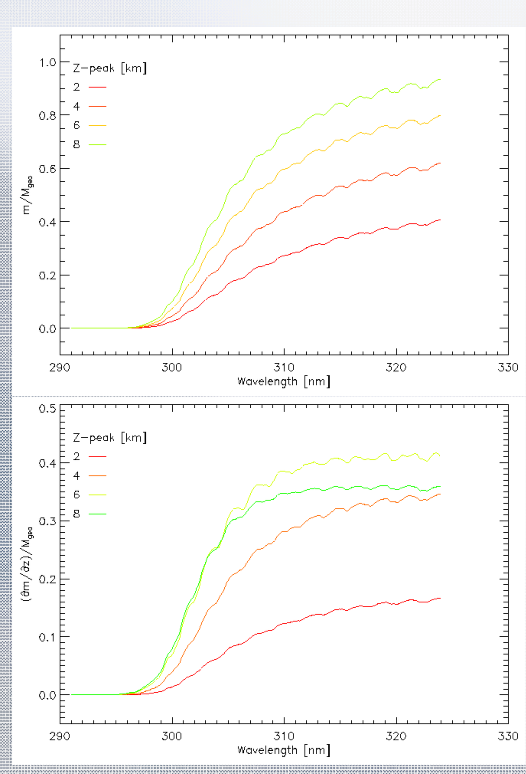

Figure 2 *Wavelength dependency of SO_2 layer air mass factor* m *and its derivative* ∂m/∂z*, normalized to the geometrical air mass factor* M_{geo}*. Colours represent different plume heights.*

Method

We derive SO_2 total vertical column density and effective SO_2 plume height by means of the direct fitting retrieval algorithm GODFIT [1]. This iterative scheme performs forward radiance and Jacobian calculations with the LIDORT radiative transfer model and contains an optimal estimation inversion scheme. **In the model atmosphere, volcanic SO_2 plumes are parameterized** in a similar fashion as described in Yang *et al*. [2010, [3]], see Figure 3.

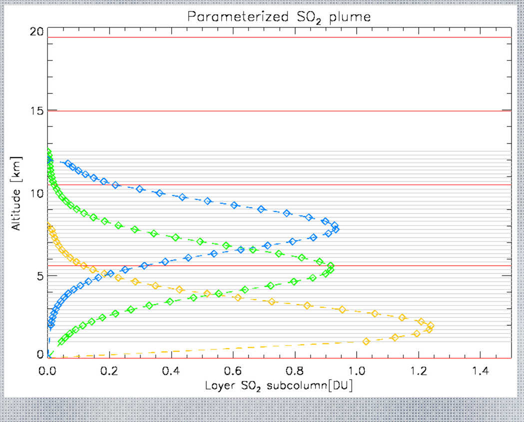

Figure 3 *Examples of SO_2 plume parameterization, for peak heights of 2, 5.5, and 8 km. Red lines show the original TOMS layering grid; for the SO_2 plumes, these layers are repartitioned (gray lines), such that the vertical air columns are preserved. Each plume is defined by a top and bottom height, peak height, and half width.*

References

[1] Lerot, C., M. Van Roozendael, J.-C. Lambert, J. Granville, J. van Gent, D. Loyola, and R. Spurr (2010), The GODFIT algorithm, a direct fitting approach to improve the accuracy of total ozone measurements from GOME, Int. J. Remote Sensing, 31, 543-550, doi: 10.1080/01431160902893576

[2] Spurr, R., J.F. de Haan, R. van Oss, and A. Vasilkov, Discrete Ordinate Radiative Transfer in a Stratified Medium with First Order Rotational Raman Scattering, J. Quant. Spectros. Rad. Transf., 2008, 109, 3, 404-425, doi:10.1016/j.jqsrt.2007.08.011.

[3] Yang, K., X. Liu, P. K. Bhartia, N. A. Krotkov, S. A. Carn, E. J. Hughes, A. J. Krueger, R. J. D. Spurr, and S. G. Trahan (2010), Direct retrieval of sulfur dioxide amount and altitude from spaceborne hyperspectral UV measurements: Theory and application, J. Geophys. Res., doi:10.1029/2010JD013982, in press.

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Results

Below we show results from retrievals of SO_2 vertical column density (VCD) and effective plume height. For the closed-loop retrievals (Figure 4) the state vector was composed of the VCD of O_3 and SO_2, the SO_2 plume height and a surface albedo. No clouds or aerosol were included. For the retrievals from GOME-2 observations (Figures 5, 6), a second order surface albedo closure polynomial was used as well as a Ring-spectrum scale factor. Here, clouds were treated as Lambertian reflectors and with use of the independent pixel approximation.

Closed-loop retrievals

Figure 4 shows results from retrievals on synthetic spectra (closed-loop retrievals) for different 'true' vertical SO_2 column densities and plume heights. As expected, **large columns or concentrations higher up in the troposphere are most easily observed.**

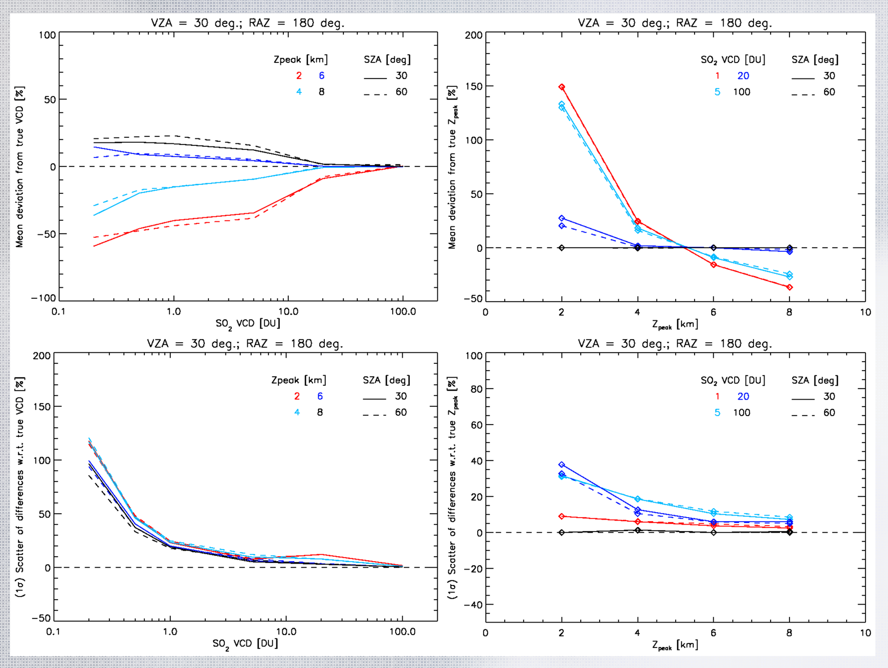

Figure 4 *Closed-loop retrieval results. Each retrieval scenario was repeated 50 times as to get reliable statistics. Left panels: mean deviation and 1-σ spread in comparison of retrieved vertical column density and true column, as function of total column amount. Colours represent different plume peak altitudes. Right panels: mean deviation and 1-σ spread in comparison of retrieved and true peak altitude, as function of plume height. Colours indicate different total column amounts. Line style indicates solar zenith angle. All results are for a Lambertian surface albedo of 0.04. For the SO_2 VCD an* a priori *value of 5 DU was used; for the peak height, 5 km was used as* a priori.

Kasatochi 8 August 2008

The high SO_2 concentrations emitted in the 2008 eruption from this Aleutian volcano were clearly observed by the METOP-1 GOME-2 instrument. Simultaneous retrieval results of SO_2 total column and plume height are depicted in Figure 5. Comparison with CALIPSO-CALIOP data of the eruption's ash cloud (not shown) indicate that our height estimates are accurate within about 2 km. In particular at the edges of the emission, **SO_2 concentrations in the GOME-2 pixels may be inhomogeneous, leading to a possible underestimation of the plume height** ('Edge effect', Yang *et al*., 2010 [3]). Near the edges of the SO_2 cloud, derived peak height values are therefore lower.

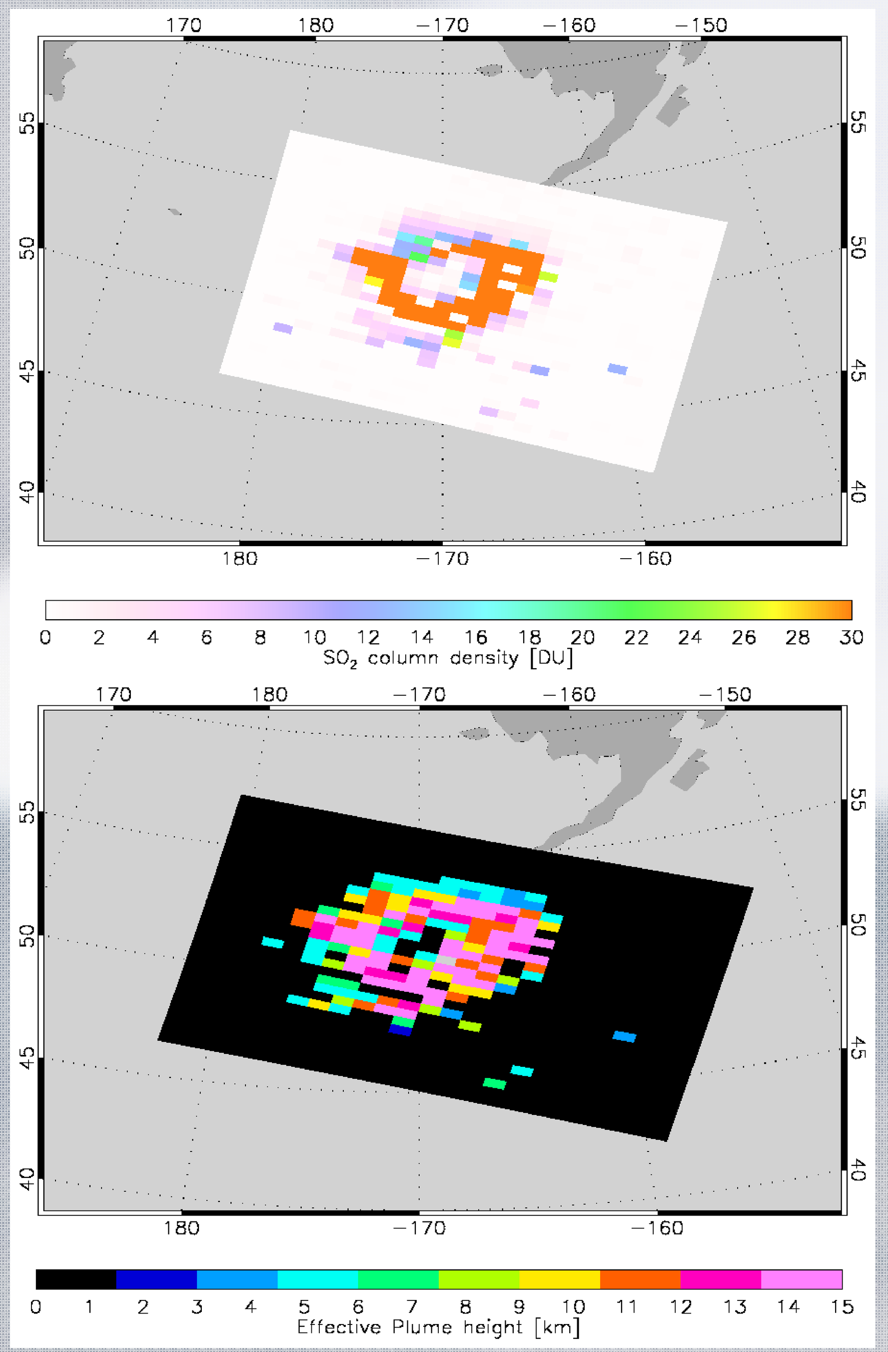

Figure 5 *SO_2 vertical column density (top) and plume height for emissions from the Kasatochi volcano on 8 August 2008.*

Eyjafjöll 9 May 2010

The GOME-2 instrument proved capable of monitoring this year's eruption for many days in a row. Deriving plume height here is more challenging, as SO_2 emission concentrations varied greatly over time and where dragged along with pressure systems in the atmosphere (Figure 6). As a result, the 'edge effect' is expected to play an important role in the derivation of SO_2 height information from Eyjafjöll measurements. When following this reasoning, the higher peak height values in Figure 6 may be the most trustworthy.

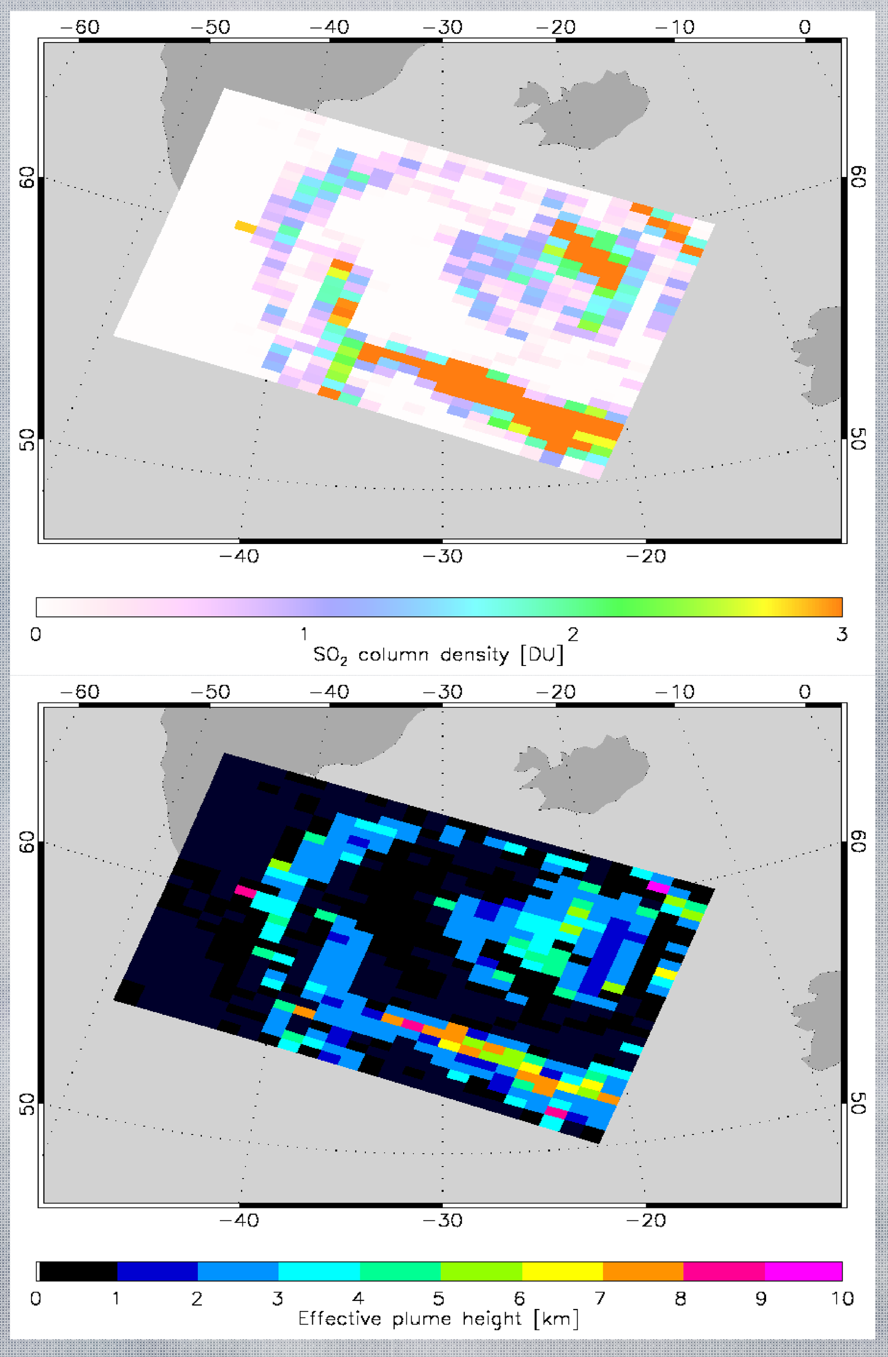

Figure 6 *SO_2 vertical column density (top) and plume height for emissions from the Eyjafjöll volcano on 9 May 2010. Inhomogeneity of the SO_2 distribution within a GOME-2 pixel may lead to an underestimate of the plume height ('edge effect').*

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