Introduction
The use of satellite measurements for SO2 monitoring has become an important aspect in the support of aviation control. Satellite measurements are sometimes the only information available on SO2 concentrations after volcanic eruptions and enhanced SO2 may indicate the presence of ash. Satellite instruments also provide information on SO2 pollution sources. SO2 columns have been derived from several UV nadir sensors (GOME, SCIAMACHY, GOME-2) with traditional DOAS methods. However, both SO2 and O3 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 O3 and SO2 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 SO2 profiles allows for the derivation of the peak height of the SO2 plume, along with the total column amounts.

Background physics
The way different layers of the atmosphere contribute to the top-of-atmosphere radiance spectrum for SO2 can be visualized by means of the vertical profile of the local air mass factor and its gradient (Figure 2). This indicates a difference between the fF2O and fF2SO2 Jacobians with respect to total column gas and gas height, as explained in Yang et al. [2010].

Put into words:

The high SO2 concentrations emitted from the Kasatochi volcano on 9 August 2008 are easier to detect.

Method
We derive SO2 total vertical column density and effective SO2 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 [2] and contains an optimal estimation inversion scheme. In the model atmosphere, volcanic SO2 plumes are parameterized on a fine layering grid (see Figure 3).

Below we show results from retrievals of SO2 vertical column density (VCD) and effective plume height. For the retrievals from GOME-2 observations a second order surface albedo closure polynomial was used as well as a ring-spectrum scale factor. Clouds were treated as Lambertian reflectors and with use of the independent pixel approximation. Aerosols were not included. For the plume height element of the state vector, a priori information has to be applied. Kasatochi, 9 August 2008 The high SO2 concentrations emitted in the 2008 eruption from this Alaskan volcano could be observed for many days.

Simultaneous retrieval results of SO2 total column and plume height for this eruption are depicted in Figure 4. Excellent agreement was found with the VCD and height derivations from Nowlan et al. [2011] for the comparison with their work we adopted an a priori plume height uncertainty of 2 km. In general, little or no altitude information will be available before the volcano is observed by GOME-2. We therefore usually adopt an a priori uncertainty of 0-5 km.

Validation
Validation of the derived SO2 plume height results is not straightforward, since for most eruptions no independent measurements (from airplanes, from ground or otherwise) exist. For the verification of our results we therefore rely on trajectory models and the spaceborne lidar instrument CALIOP on the CALIPSO platform. The application of both methods is illustrated below.

Nabro, 15 June 2011
With a violent offset on the late night of 12 June this eruption provided the highest levels of SO2 ever detected from space. Within days the gases had spread over large areas and also into Asia and Europe could be followed for several weeks. Figure 5 shows SO2 VCD and plume height results for 15 June 2011. From the figure we can tell that derived plume height values are most reliable close to the source (where concentrations are high) or for plumes at higher altitude, which are easier to detect.

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