Retrieval of Volcanic Ash and Ice Cloud Physical Properties Together with Gas Concentration from IASI Measurements Using the AVL Model

S. Kochenova, M. De Mazière, N. Kumps, S. Vandenbussche and
T. Kerzenmacher

*Belgian Institute for Space Aeronomy (BIRA-IASB), Atmospheric Composition Department,
Ringlaan 3, Brussels, 1180 Belgium*

Abstract. Observation and tracking of volcanic aerosols are important for preventing possible aviation hazards and determining the influence of aerosols on climate. The useful information primary includes the concentration, particle size and altitude of aerosol load. Moreover, volcanic eruptions are usually accompanied by strong emissions of SO_2 and enhanced concentrations of H_2O in the atmosphere. Volcanic ash particles can also catalyze the formation of ice clouds by serving as cloud nuclei. Hyperspectral infrared sounders, such as IASI (Infrared Atmospheric Sounding Interferometer), have proven to be powerful tools for capturing volcanic aerosol and ice cloud signatures and enhanced volcanic gas concentrations. Information on atmospheric constituents is extracted from such hyperspectral measurements with the help of radiative transfer (RT) codes capable of solving both direct and inverse RT problems.

We will demonstrate the retrieval of aerosol and ice cloud physical properties together with gas concentration from IASI measurements with the help of the AVL RT model. AVL is one of the ‘code combination packages’ which are becoming more and more popular in the scientific domain. It consists of several codes, each of which handles a specific set of physics-related tasks. The codes function smoothly as a whole due to the use of a special interface. AVL is perfectly suitable (i) to model the propagation of UV-visible-IR radiation through a coupled atmosphere-surface system for a wide range of atmospheric, spectral and geometrical conditions; and (ii) to retrieve vertical gas profiles and aerosol concentration through the use of its embedded retrieval algorithm on the basis of an optimal estimation method (OEM).

The retrievals are performed for IASI measurements (radiance, Level 1C product) carried out over Eyjafjallajökull volcano, Iceland, in April 2010.

Keywords: Atmospheric radiative transfer, Volcanic aerosols, Aerosol properties retrieval.
PACS: 92.60Hf, 92.60Mt, 92.60Vb

IASI MEASUREMENTS

IASI is one of the two atmospheric chemistry passive remote sensors installed on the MetOp-A meteorological satellite launched by EUMETSAT in October 2006 in a polar orbit. It covers fully the spectral range from 645 to 2760 cm^{-1} and is characterized by a low instrumental noise [1]. Its standard radiance (Level 1C) product, which is of interest here, is apodized with the IASI spectral response function [2] and provided in the form of 8461 radiance channels with a width of 0.25 cm^{-1} each. The frequency of IASI’s global Earth coverage is twice a day.

AVL RT MODEL

Information on atmospheric constituents is extracted from IASI measurements with the help of the advanced AVL (ASIMUT-(V)LIDORT) RT model capable of solving both direct and inverse problems. The model consists of several codes, each of which handles a specific set of physics-related tasks. Molecular absorption is calculated by the high-resolution line-by-line code ASIMUT, developed by A.C. Vandaele and others at BIRA-IASB, Belgium. ASIMUT also handles general input/output, instrument convolution/apodisation, optional graphic representation of the results (with the help of incorporated MATLAB functions) and a retrieval algorithm on the basis of Rodger’s OEM [3]. Volcanic ash and ice cloud properties are calculated using the SPHER code developed by M. Mishchenko et al. [4]. The RT problem is solved by the advanced linearized code VLIDORT, created by R. Spurr [5]. VLIDORT also generates fields of analytical derivatives of radiance (Jacobians) with respect to different aerosol/ice cloud parameters, required as input to the ASIMUT retrieval algorithm. The codes function smoothly through the use of a special interface developed by Kochenova and others at BIRA-IASB, Belgium.

Radiation Processes in the Atmosphere and Ocean (IRS2012)
AIP Conf. Proc. 1531, 103-106 (2013); doi: 10.1063/1.4804718

RETRIEVAL OF GAS PROFILES

Volcanic eruptions are sometimes accompanied by strong emissions of SO_2 and enhanced concentrations of H_2O in the atmosphere. IASI volcanic ash and ice cloud signatures are usually characterized by an overall drop in the baseline (in addition to their unique spectral features) within 800-1200 cm^{-1} – a spectrum range that includes an O_3 absorption band (980-1070 cm^{-1}). For these reasons, the retrieval of volcanic ash and ice cloud parameters is usually accompanied by the retrieval of SO_2, H_2O and O_3. Here we demonstrate an example retrieval of O_3 concentration from IASI spectrum 16-09 (track 16, footprint 09) with the help of AVL. The interference with H_2O lines is minimal in the selected spectrum range.

The retrieval was performed on the basis of the OEM developed by Rodgers [3]. The O_3 climatological profile (subarctic winter) was used as a priori. The covariance matrix was built following the approach described in [6]. The matrix was chosen to be diagonal with each diagonal element identical and equal to the conservative value σ_e = 7×10^{-8} $Wcm^{-2}cmsr^{-1}$, which is about three times the IASI radiometric noise. The retrieval was performed over the whole vertical scale, considering 0-23 km and 47-80 km as two wide layers and applying a 2-km thickness grid between 23 and 47 km. The retrieved profile was then interpolated over the climatological altitude grid. Figure 1 shows the results of the retrievals.

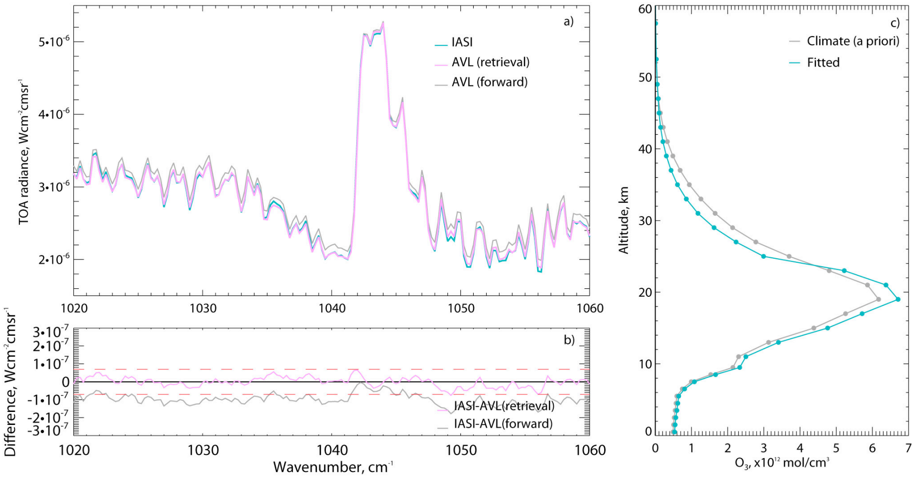

FIGURE 1. Retrieval of O_3 vertical profile from IASI spectrum 16-09 collected in proximity of the Eyjafjallajokull volcano on 15 April 2010. a) IASI radiance vs. AVL forward (with the a-priori O_3 profile) and retrieved radiance (with the retrieved O_3 profile). b) Absolute difference between IASI radiance and AVL forward and retrieved radiance. The horizontal dashed lines indicate the level of radiometric noise used to estimate the quality of this retrieval. c) A priori and fitted O_3 profiles.

ICE CLOUD CASES

Retrieval of Ice Cloud Concentration

Ice clouds produce a unique signature that presents itself as a distinctive slope in the IASI spectrum range of 800-1000 cm^{-1}, when the radiance is plotted in the BT (Brightness Temperature) units.

The retrieval of ice particle concentration is illustrated for IASI spectrum 16-11 in Fig. 2. It was also performed with the help of Rodgers's OEM. The ice cloud was modelled as a layer of spherical particles located between 11 and 12 km, described by a gamma size distribution with effective radius r_{eff} = 15.0 μm and variance v_{eff} = 1/9. The r_{eff} value is the one that provides the best inclination fit as defined by a sensitivity study, analogous to that described in [7]. The cloud altitude and v_{eff} were as suggested in [8]. The refractive indices for the ice cloud were those of water ice determined in [9] for 210 K.

AVL was prompted to perform a retrieval-retrieval-forward sequence. First, it retrieved the H_2O vertical profile from spectrum 16-09, which showed no aerosol signature (and thus allowed accurate profile retrieval); second, this retrieved profile was used for the ice particle concentration retrieval in the range of 800-830 cm^{-1} from spectrum 16-11 (Fig. 2a,b); third, both retrievals were used for forward simulations in the range of 800-1000 cm^{-1} (Fig. 2c). The a priori ice particle concentration was assumed to be equal to a reasonable value of 0.35 part/cm^3. The retrieved concentration is 0.43 part/cm^3 (Fig. 2d). The modeled and measured radiance values agree well within the specified error limit.

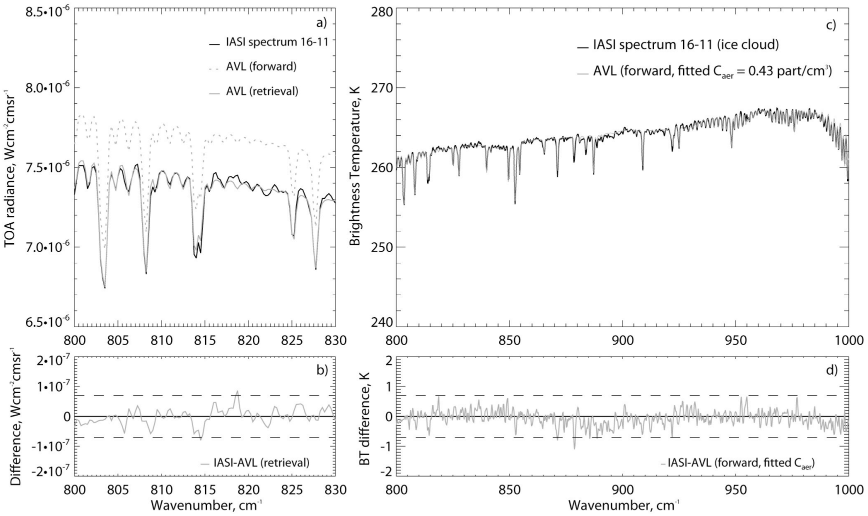

FIGURE 2. Retrieval of ice cloud concentration from IASI spectrum 16-11 collected in proximity of the Eyjafjallajokull volcano on 15 April 2010. a) IASI radiance vs. AVL forward (with a priori C_{aer}=0.35 part/cm^3) and retrieved (with fitted C_{aer}=0.43 part/cm^3) radiance. b) Absolute difference between IASI radiance and AVL retrieved radiance. The horizontal dashed lines indicate the level of radiometric noise (7x10^{-8} Wcm^{-2}cmsr^{-1}) used to estimate the quality of this retrieval [6]. c) AVL forward simulations with the retrieved concentration. d) Absolute difference between the AVL and IASI radiance.

Sensitivity to the Radius and Concentration

In the case of ice cloud measurements, the absorption of ice decreases from 800 to 1000 cm^{-1}. The rate of this decrease depends on ice particle size and concentration (Fig. 3). Thus, ice cloud concentration C_{aer} and particle effective radius r_{eff} should be retrieved simultaneously.

We should note that (i) it is difficult to distinguish between the influence of the ice cloud layer altitude and C_{aer}, because both of them diminish the radiance plotted in BT units; (ii) C_{aer} depends on the assumed geometrical thinkness of the cloud. To overcome these limitations, it might be more convenient to take altitude and geometrical thickness data from external measurements, e.g., from LIDAR-ceilometer measurements (www.earlinet.org), when they are available. For the example presented here, the value of C_{aer} is only valid for the assumed thickness of 1 km.

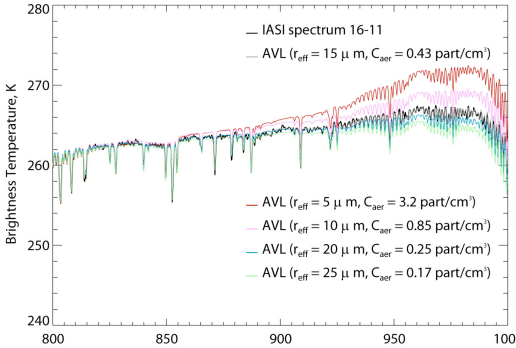

FIGURE 3. Simulation of IASI spectrum 16-11 with 5 different C_{aer} and r_{eff} values.

Simultaneous retrievals of C_{aer} and r_{eff} will be possible with the help of the new linearized MIE and T-MATRIX codes developed by R. Spurr et al. [10]. These codes are capable of calculating Jacobians (radiance derivatives needed for retrieval) of aerosol optical properties w.r.t. particle refractive index, size distribution & shape parameters.

VOLCANIC ASH CASES

Volcanic ash particles can catalyze the formation of ice clouds by serving as cloud nuclei. IASI spectra containing volcanic ash signature are characterized by descending (800-1000 cm^{-1}) and ascending (1070-1200 cm-^{1}) slopes when the radiance is plotted in BT units. For forward modeling we assumed one volcanic ash layer at 9-10 km (extracted from Lidar-ceilometer data) and log-normal distribution of particles with r_g = 4.0 μm and σ_s = 2.02 μm. The retrieval scheme is analogous to that for ice clouds plus the retrieval of O_3 concentration from IASI 16-09. As an example, we show the retrieval of C_{aer} in the spectrum range of 1070-1100 cm^{-1} (Fig. 4).

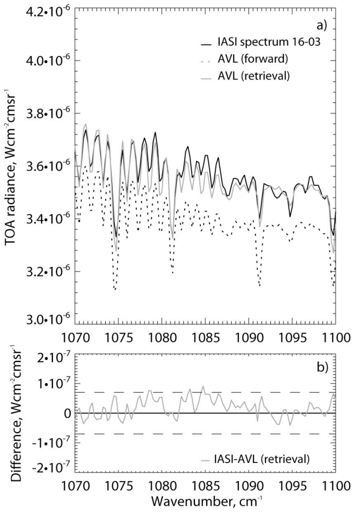

FIGURE 4. Retrieval of volcanic ash concentration from IASI spectrum 16-03. a) IASI radiance vs. AVL forward (modelled with a-priori C_{aer}=4.0 part/cm^3) and retrieved (modelled with retrieved C_{aer}=2.0 part/cm^3) radiance. b) Absolute difference between the IASI radiance and AVL retrieved radiance.

ACKNOWLEDGMENTS

The research presented here was carried out within the framework of the 'Radiative Transfer' project sponsored by the Solar Terrestrial Centre of Excellence (STCE), Brussels, Belgium.

REFERENCES

1. C. Clerbaux et al., *Atmos. Chem. Phys.* **9**, 6041-6054 (2009).
2. E. Péquignot et al., Status of IASI performances after 3 years in orbit. 2nd IASI conference, Annecy (France), 25-29 January (2010).
3. C. D. Rodgers, *Inverse Methods for Atmospheric Sounding: Theory and Practice*, Singapore: World Scientific Publishing Co. Pte. Ltd., 2000, 240 pp.
4. M.I. Mishchenko, L.D. Travis and A. A. Lacis, Scattering, Absorption, and Emission of Light by Small Particles. Cambridge: Cambridge University Press, 158-165 (2002).
5. R. Spurr, *JQSRT* **102**, 316-342 (2006).
6. A. Boynard et al., *Atmos. Chem. Phys.* **9**, 6255-6271 (2009).
7. L. Clarisse et al., *Atmos. Chem. Phys.* **8**, 7723-7734 (2008).
8. L. Clarisse et al., *Appl. Opt.* **49**, 3713-3722 (2010).
9. M. L. Clapp, R. E. Miller and D. R. Worsnop, *J. Phys. Chem.* **99**, 6371-6326 (1995).
10. R. Spurr et al., *JQSRT* **113**, 425-439 (2012).