

Interactive comment on “Retrieval of ash properties from IASI measurements” by Lucy J. Ventress et al.

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Response to Anonymous Referee #1

Please note that all page and line references in the responses refer to the updated manuscript uploaded as supplementary material.

General comments: The authors present an interesting piece of work towards a better characterization of volcanic ash plumes from space. They use hyperspectral IASI measurements in the context of an optimal estimation scheme for assigning the most probable solution in terms of AOD, effective radius and ash layer altitude. Unfortunately the paper lacks a very important piece of information, which is essential to judge the quality and also the novelty of the presented approach. I was not able to find information about the methodology used by the authors to derive the optical properties of the

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ash, which are essential input to the radiative transfer calculations. The authors give hints that they assume spherical particles and mono-modal lognormal distributions. So I assume the optical properties have been calculated using Mie theory? With which code (there can be large differences!)? Which refractive indices have been used - and how have they been spectrally interpolated (as there are not many refractive indices at the spectral resolution of IASI)? What parameters for the lognormal distributions have been assumed to end up with the presented effective radii?

The authors acknowledge that these are important factors that have been left out. The paper now includes from p.7 l. 25 ‘The emissivity, reflectance and transmittance of the ash layer are functions of the state vector elements, optical depth, τ , effective radius, r_{eff} , and plume top height, h as well as the observation geometry. Computational efficiency is optimised by pre-computing these properties of the ash layer using DISORT (Stamnes et al., 1988) and storing the results in look-up-tables (LUTs), which are linearly interpolated spectrally to the appropriate values. The spectral aerosol optical properties (extinction coefficient, single scattering albedo and the phase function) for ash are calculated using Mie theory (Grainger et al., 2004; code available at: <http://www.eodg.atm.ox.ac.uk/MIE/index.html>) and external mixing. The ash particles are assumed to be spherical with a mono-modal log normal aerosol size distribution, which has been shown to be a suitable representation of the size distribution of airborne volcanic ash (Wohletz et al., 1989). The distribution is characterized by a spread of 2 (Wen and Rose, 1994b; Yu et al., 2002; Rybin et al., 2011; Pavolonis et al., 2013b) and the mode radius is translated to obtain different effective radii. The refractive index used in this paper is from measurements of ash from the Eyjafjallajökull eruption (Peters). These properties are calculated every 5 cm^{-1} in the spectral range used by the retrieval, across a range of effective radii from $0.01\text{--}20 \mu\text{m}$, to create the input for DISORT. Ignoring multiple reflections ...’

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Without this information it is hard to understand what exactly are the capabilities of the method and which uncertainties may be hidden in the input assumptions. Consequently the manuscript requires major revisions before being considered for publication in AMT.

Specific comments: p.1 l. 2: When the authors write "such as IASI", does that mean that the method as it is can be applied to AIRS or VIIRS? In that case not all IASI bands would be used (as AIRS and VIIRS lack significant parts of the specified range) and a description of the used IASI channels would be missing. Otherwise please make clear that the method has been developed for the use with IASI only.

The method has currently only been applied to IASI. However, it could be adapted for use with other hyperspectral instruments, which would of course not necessarily use identical spectral bands. This has been made clearer in the text. The abstract now reads 'A new optimal estimation algorithm for the retrieval of volcanic ash properties has been developed for use with the Infrared Atmospheric Sounding Interferometer (IASI).' and at p.2 l.12 reads 'Presented here is a new optimal estimation algorithm for the retrieval of volcanic ash properties that has been developed for IASI, which could be further adapted for use with other hyperspectral satellite instruments.'

p.1 l. 13: Please introduce abbreviations the first time they occur (RMS). Moreover, "RMS" is rather unspecific. What exactly is meant? Root Mean Square Difference (RMSD)? Root Mean Square Error (RMSE)?

This has been corrected and defined as RMSE

p.1 l. 14: Please specify what exactly is meant by "low optical depth". $AOD < 0.1$? $AOD < 0.5$?

This has now been made more specific by inserting that it refers to $AOD < 0.1$.

p.3 l.1: Typically the aerosol which can be detected by IASI is dust, not sand. "Sand"

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denotes particles $> 63\mu\text{m}$, which are bound to the lowest part of the boundary layer due to the strong gravitational forces (unless in heavy sand storms, where turbulent forces can uplift even sand particles to larger altitudes - but they deposit rather fast after ceasing of the turbulent motions).

This is an error in the text, it was intended to read 'dust' and has been corrected.

p.3 l.1: "IASI level 1c radiance data"

Corrected in the text.

p. 4 l. 4: Is there any indication of the assumed orthogonality between ash signal and other signals in the spectra from theoretical considerations? If they are not orthogonal, the basic assumption behind the presented approach is at risk, so this orthogonality should be somehow derived or at least be motivated in a convincing way (this does not mean that I do not believe in that orthogonality!).

The referee is correct, that orthogonality is required for the method to work. To demonstrate the difference between an ash signal and the non-ash signal we carried out a retrieval on a synthetic clear sky scene. If the signals were not orthogonal we would expect to retrieve ash values even though no ash was present. Such a retrieval gives an $\text{AOD} \sim 0.2$ a tiny (and negative) effective radius and the height of the plume is at the surface. The retrieval does not converge quickly and has a high cost due to attempting to fit an ash layer where there is none and therefore it would not pass the quality control. This indicates orthogonality but does not prove it. For the purposes of the paper the text has been edited to be more specific about the component retrieved. p.4 l.16 'Assuming that the state of such variables are of no interest (in this problem) and the spectral signal of these variables are orthogonal to the ash signal, including these spectral signatures within the error covariance means there is no need for them to be retrieved nor their variance to be accounted for in the forward model of the atmosphere, thus allowing the problem to be simplified. More specifically, the assumptions

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in this method allow the retrieval of the orthogonal component of the retrieval parameters.'

p. 4 l. 7: I would like to see a small discussion about the assumed distribution of the brightness temperatures and especially about the assumed distribution of their uncertainties. I guess the authors assume the uncertainties being distributed normally, otherwise one could raise severe concerns about the validity of eq. (3). Such an assumption should be clearly stated.

Yes, it is assumed that the brightness temperature uncertainties are distributed normally. This has now been explicitly stated in the text.

p. 4 l. 15: "With no volcanic ash signal" or "with no volcanic ash detection"? That is significantly different!

This has been made clearer in the text. They are days that there is no known volcanic activity. p.4 l. 29 'Initially, when selecting the IASI scenes to include in the creation of the covariance matrix, only scenes from days with no known volcanic activity were used.'

p. 6 l. 8: Do the authors think there is sufficient information about ash type (what exactly do the authors mean by that word?) from below the O₃ attenuation? I have some doubts...

The authors agree that this line is misleading and therefore it has been removed. It is hoped that ash type (i.e. ash derived from different magma composition) may be discerned from the extinction, which is at a maximum in the O₃ band.

p. 6. l. 8: What about SO₂? Are there any (important) SO₂ absorption bands within the selected wavenumber range?

There is an SO₂ band within the range used in the retrieval but the major absorbing channels are avoided in the channel selection, meaning there will be only a weak signal in those that are used.

p. 7 l. 15: There are a lot of other parameters to be assumed in order to derive the mass loading. First of all the assumed particle sphericity is a strong and definitely wrong assumption. That could be overcome by assuming an asphericity factor, which would impact on the volume estimation from the effective radius. With that regard - for nonspherical particles it must be defined if the effective radius is cross-section equivalent or volume equivalent, which can be totally different numbers. Then, in order to get to an estimate for the mass loading, the extinction efficiency needs to be known (estimated or assumed). For volcanic ash particles in the presented size range that is definitely not 2.0 ...

The authors agree that the ash mass calculation is not a simple one and realise that no reference was provided for our calculation. This has now been added (see p.9 l.3 (see <http://eodg.atm.ox.ac.uk/user/grainger/research/aerosols.pdf>)). The authors also note, that the sphericity assumption is indeed not perfect but it has been shown that an assumption of spherical particles with a log-normal size distribution is a suitable representation of the size distribution of airborne volcanic ash (Wohletz et al., 1989). The reference has been added to text). Here we are merely stating that an ash mass can be calculated and this paper does not aim to prove the validity of the mass generated or any method to do so. Therefore, it is felt that further description is not needed.

p. 9 l. 3: "Degrees of Freedom for Signal (DFS)" - There also exist a lot of other definitions and concepts of degrees of freedom.

This has been corrected in the text.

p. 9 l. 6: I would suggest to shortly explain the concept of DFS for the readers not familiar with it. Especially what we can learn from the numbers (by the way: why do the authors not show the DFS in Fig. 5?).

A description has been added in the text: see p.9 l.10 'The results show the uncertainties in the retrieved parameters and the Degrees of Freedom for Signal

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(DFS) within the retrieval for different scenarios. The DFS is a figure of merit that expresses the information contained in a retrieval by compressing the information within the retrieval error covariance matrix into a single scalar quantity. Essentially, it provides the number of independent pieces of information available in an estimate of the state.’ The authors have not shown the DFS in Fig. 5 as it was not deemed necessary given the information provided regarding the DFS in section 4.

p. 9 l. 10: "Interestingly, and perhaps unexpectedly, the surface temperature uncertainty improves at the highest altitudes." To be honest, I do not understand this sentence. What exactly is at highest altitudes? The ash layer? I do not assume that surface temperature is at different altitudes? So please reformulate this sentence.

The sentence has been restructured to make sense. The altitude referred to the height of the assumed ash layer. p.9 l.20 ‘the surface temperature uncertainty improves when the ash layer is at the highest altitudes.’

p. 9 l. 15: This is well known for quite a while now (for example S.A. Ackerman, 1997: Remote sensing aerosols using satellite infrared observations, J. Geophys. Res., 102, 17069-17079).

The reference has been inserted.

Section 5.1: Is the MODIS instrument described as input for ORAC? Then please make subsections 5.1.1-5.1.2 one subsection. Otherwise, if MODIS products are used, describe them (which algorithm, which collection, how they are aggregated).

The MODIS data is used as an input to the ORAC algorithm so the sections have been combined and re-titled ‘MODIS Retrieval Method’

p. 12 l. 5: How is $11\mu\text{m}$ AOD derived? Here again the description of the derivation of optical properties and basic assumptions is missing. Without that the reader is not able to understand how $11\mu\text{m}$ AOD and other ash layer parameters are derived.

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A more detail description of the ORAC algorithm has been included including information on the optical properties and how the $11\mu\text{m}$ AOD is derived. p.13 I.10 ‘For MODIS ash retrievals ORAC uses measurements of solar reflectance in bands 1, 2 and 6 (0.65 , 0.86 and $1.64\mu\text{m}$) and thermal brightness temperature in bands 20, 27, 28, 29, 31, 32, 33, 34, 35 and 36 (3.8 , 6.7 , 7.3 , 8.6 , 11.0 , 12.0 , 13.3 , 13.6 , 13.9 and $14.2\mu\text{m}$). The primary retrieval parameters include ash optical thickness at 550 nm , effective radius of a log-normal ash particle size distribution, ash plume top pressure and effective radiating temperature. Parameters derived from these include the ash optical thickness at $11\mu\text{m}$, derived from the optical thickness at 550 nm and the effective radius; the ash plume top height and temperature, derived from the cloud top pressure and input meteorological profiles; and the ash mass loading, derived from the optical thickness at 550 nm , the effective radius and an assumed ash density of 2.6 g cm^{-3} (Neal et al., 1994).

The ash particles are assumed to be spherical with a log-normal size distribution and the size distribution averaged spectral optical properties (extinction coefficient, single scattering albedo and phase function are calculated using Mie theory. Since the width of the distribution is not a retrieval parameter it must be assumed and a standard deviation of 2.0 is the value adopted for the ORAC retrieval. The complex index of refraction must also be assumed for which we use values measured from Eyjafjallajökull ash samples (Peters). These properties are the same as those assumed in the IASI retrieval.

The ash optical properties are further used as input to the plane parallel radiative transfer solver DISORT to compute scalar spectral reflection, transmission and emission operators used in a “fast” forward model, details of which are described in McGarragh et al. (2016), and stored in LUTs as a function of the retrieved $0.55\text{-}\mu\text{m}$ optical thickness and effective radius, in addition to the solar and satellite geometry. The optical thickness at $11\mu\text{m}$ is obtained directly from the ratio of the extinction coefficient at $11\mu\text{m}$ to that at $0.55\mu\text{m}$. The ash plume

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is assumed to be infinitely thin geometrically allowing for a full decoupling of the ash radiative transfer from that of the clear-sky for which the transmittance and emission are computed with RTTOV from meteorological pressure, temperature, humidity and ozone profiles from the ECMWF ERA-Interim reanalysis product (Dee et al., 2011). Molecular (Rayleigh) scattering is computed according to Bates (1984) from the pressure and temperature profiles. Finally, the surface is characterized with a bidirectional reflectance distribution function (BRDF) for both land (Schaaf et al., 2002) and ocean (Sayer et al., 2010). Specific details regarding the sources of uncertainty are discussed in Thomas et al. (2009b), Sayer et al. (2011) and McGarragh et al. (2016).'

p. 12 l. 20: It would be good to present the number of coincidences alongside.

This number has been added to the text. p.14 l.10 'The data shown is from the Eyjafjallajökull eruption in 2010 and only the retrievals that pass the imposed quality control measures for both algorithms are shown (73 coincidences).'

p. 14 l. 4: Does that mean that for the aircraft data bimodal lognormal distributions are assumed? It would be good to see the parameters for both modes along with the effective radii in table 1.

Yes the aircraft observed bimodal distributions and fit the geometric mean diameter, standard deviation and relative weights. These values are taken from Turnbull et al. (2012) and have been added to the table.

p. 15 l. 15: I have no hint from the manuscript where the authors derive this finding from. It would help to have the IASI derived effective radii averaged for the flight areas as well in table 1 (or at least mentioned in the text) or to have similar histograms as that in figure 7 from the aircraft data.

The authors are not in possession of the data to provide histograms of the aircraft measurements. However, the mode value of effective radius for the entire plume

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observed by IASI has been added to the table for comparison. It was tested limiting the data to only within 50km of the aircraft track but this made no difference to the observed mode.

Figure 7: What is the bin size of the histogram? Is it really necessary to have such small bins (I assume the bin size is well below the assumed accuracy of the retrieval?)?

The authors agree that the bin size was too small and have increased it to $0.1 \mu\text{m}$

Figure 8: What exactly is colocated with what here? Are the black triangles IASI cloud top height? Does the CALIOP derived cloud top height include aerosol layers? More explanation is necessary.

It has been made clearer in the caption that the triangles are the CALIOP derived height at the locations that are coincident with an IASI measurement. Fig. 8 Caption: 'An example of the derived CALIOP cloud top heights are shown (as the solid line) for an overpass of Grimsvötn on the 22nd May 2011. The CALIOP derived height at locations co-located with IASI pixels are illustrated by triangles and the background shows the backscatter seen by CALIOP.'

p. 16 l. 20: How small is "small"? As before: it would be good to present numbers. Even if they are small: everyone acknowledges that the coincidences are not widespread; providing these numbers does the manuscript no harm.

The numbers have been added and the sentence now reads: 'Due to the narrow swath of the CALIOP instrument, there are only 8 coincidences (119 pixels in total) between the two satellite datasets where the CALIOP track intersects with the volcanic plume seen by IASI.'

Figure 10 and 11: I would appreciate to have basic statistics (number of coincidences, correlation coefficient, bias, RMSD) together with the plots - either annotated to the plot or mentioned in the caption or the text.

Further statistics have been added to the text. p.19 l.3 '...The outliers are re-

flected in the RMSE value for the height comparison, which is 2.5 km ($r = 0.31$). However, upon removing the optically thick outliers from the scene, this reduces the RMSE difference to 0.8 km and increases the correlation to $r = 0.41$. The comparison for another well co-located scene is also shown in Fig. 10 for the 11th May 2010, which again shows good agreement with $r = 0.46$ and an RMSE value of 0.9 km.

Comparisons are not shown for all scenes individually, however, Fig. 11 shows the comparison for all points across all scenes. Some scenes have far fewer co-located pixels but do confirm that there is agreement between the CALIOP and IASI derived altitude range with the values largely occurring between 2 and 6 km. Despite good correlation in individual scenes, it is very low for all pixels, $r = 0.12$, with RMSE of 2.1 km. Visually, it can be seen that there are cases where the retrieval fails to fully capture the higher altitude plumes and there is an underestimation of the plume top height (as previously described), however, this is for only two of the scenes and given the time difference between the satellite overpasses,...'

p. 19 l. 10: I am not really convinced that this claim is true. What about the uncertainties of the ash optical properties? Where in the optimal estimation scheme are they reflected? Otherwise it is just not correct that all inaccuracies are accounted for.

The text is perhaps misleading and has been altered to correct for this. The uncertainties accounted for are those in the radiative transfer forward model, not the ash optical properties used in the Mie code. p.22 l.2 '... This ensures that all inaccuracies in the radiative transfer modelling of the IASI spectrum, caused by lack of knowledge of the background atmospheric conditions (e.g. atmospheric profiles) or imperfections in the radiative transfer calculation (e.g. spectroscopy) are accounted for within the covariance matrix. Separate covariance matrices have been created using only clear-sky or cloudy scenes, where the latter contains the variance caused by the impact of meteorological

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cloud. It should be noted that this does not account for errors in the ash optical properties. ...'

Please also note the supplement to this comment:

<http://www.atmos-meas-tech-discuss.net/amt-2016-143/amt-2016-143-AC1-supplement.pdf>

Interactive comment on Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2016-143, 2016.

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