Atmos. Meas. Tech. Discuss.,
doi:10.5194/amt-2016-143-AC2, 2016

Atmospheric Measurement Techniques Discussions
Open Access

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

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Received and published: 1 August 2016

Response to Anonymous Referee #2

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

The manuscript describes a method for ash property retrievals using IASI measurements. The manuscript is well-written, but more details of the methodology and analysis are desirable and should be included before publication. Suggestions for improvements are given below.

- Surface temperature retrieval: In the abstract and elsewhere it is mentioned that the surface temperature is retrieved. However, in the manuscript no surface tem-

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Discussion paper

perature retrievals are described. This should be one of the retrieved quantities that is easiest to compare with independent measurements or weather forecast models. Hence, please include a discussion and presentation of the surface temperature retrievals and comparison with relevant data.

The authors have not shown the output of the 'surface temperature' retrieval as there is no resource that it can be easily compared to. In reality, the retrieved parameter is the 'effective radiating temperature' not surface temperature and therefore a comparison against, for example, ECMWF data would be meaningless. It is used in the retrieval to help ground the retrieval but the output is not directly applicable to a real quantity. The authors feel that, in retrospect, it is perhaps misleading to refer to it as a surface temperature and therefore have replaced each occurrence with 'effective radiating temperature'.

- Introduction, general comment: A majority of earlier works on satellite ash detection and retrieval use broad band instruments such as SEVIRI, MODIS, AVHRR etc. Please include a paragraph about what are the advantages and disadvantages with hyperspectral instruments. For example: hyperspectral instruments provide more spectral information and may thus potentially retrieve parameters that otherwise have to be assumed in retrievals using broad band instruments. On the other side, hyperspectral instruments typically have larger footprints than the broadband instruments. For example compare AVHRR and IASI which are on the same satellite. It should also be emphasized that you are retrieving the altitude of the plume height. The lack of plume height information is a major limitation in most split-window and similar techniques.

The following comparison has been added to the text. p.2 l.6 'These methods have been applied to both hyperspectral and broad band satellite instruments, each of which have advantages and disadvantages. For example, IASI, on board MetOp-A, has a wealth of spectral information with over

8000 wavenumber channels allowing the potential to retrieve many parameters. Whereas the Advanced Very-High Resolution Radiometer, AVHRR, a broad band instrument, has only 6 channels to extract information from meaning more assumptions must be made about the state. However, the spatial coverage of AVHRR is much greater than IASI with a footprint of ~ 1 km compared to IASI's 12km footprint giving far more measurements within a volcanic plume. Presented here is a new optimal estimation algorithm for the retrieval of volcanic ash properties that has been developed for IASI to take advantage of its spectral information, which could be further adapted for use with other hyperspectral satellite instruments.'

- Page 2, lines 5-6: Of the papers mentioned here, only the paper by Clarisse et al. (2010) use hyperspectral data, while the rest use broad band data. As this paper use IASI data it should be clearly stated that the other papers use the mentioned techniques on broad band data with limited spectral information. You may also want to mention that hyperspectral data may be used to retrieve the ash refractive index, see Ishimoto et al. (2016).

  The authors believe this point has now been addressed in the above paragraph.

- Page 2, line 20: fr $\rightarrow$ für.

  This has been corrected in the text.

- Page 3, line 9: To make the manuscript self-contained, please include one or two sentences describing how the ash detection is done and IASI pixels flagged.

  The following description has been added to the text. p.3 l.17 '... flags IASI pixels for the presence of volcanic ash. The detection procedure looks for departures in a spectrum from an expected background covariance. An ensemble training set of IASI data, assumed to contain no extraordinary

ash concentrations, is used to create a generalised error covariance matrix that contains the spectral variability caused by interfering trace species and clouds as well as the IASI instrument noise. A least squares fit retrieval is carried out to retrieve the ash optical depth at three assumed altitudes; 400 ***mb,*** 600 ***mb and*** 800 ***mb. The pixel is flagged if the ash optical depth at any of the altitudes passes a given threshold. In previous work, the presence of volcanic*** SO_2 ***has been used as a proxy ...'***

- Page 16, line 9: Please state which parameters are not retrieved but assumed and included in b. How does the assumed values of these parameters affect the retrieval error?

  The parameters that are not retrieved, such as temperature profile, gas profiles, spectroscopy etc. are all mentioned in the following section regarding the error covariance matrix, which explains why they are not retrieved and how their uncertainties are accounted for within the covariance. The authors therefore feel that a repetition of that here is unnecessary.

- Page 3, line 23: the the → the.

  This has been corrected in the text.

- Page 3, line 24: Please state your convergence criteria and maximum number of iterations.

  These numbers have been added to the text. p4. l.5 '...the Levenberg-Marquardt-Press method is implemented, which numerically iterates the retrieval until a convergence criteria is satisfied (a positive or negative change in the cost of 1), or a maximum number of iterations is reached (default is 10)...'

- Page 4, lines 4-5: It is assumed that "these variables are orthogonal to the ash signal". May you please state what "these variables" are in order of importance?

You mention clouds. Can you justify that ash clouds and for example liquid water clouds are orthogonal to each other using the difference in their optical properties?

The method itself requires orthogonality for it 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 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 in this method allow the retrieval of the orthogonal component of the retrieval parameters.'

- Page 4, lines 20: Please clarify if the forward model was cloudless also for the cloudy covariance matrix. Would it be possible to make covariance matrices for each effective cloud temperature and would you expect this to improve the retrieval?

This has been clarified in the text. The forward model is always assumed to be cloudless during the retrieval (only an ash layer) with the uncertainty due to a meteorological cloud contained in the covariance matrix - which is the difference between clear sky forward model simulations and potentially

cloudy IASI scenes. p.5 l.6 'In both instances the forward model assumes a clear-sky scene scene.'

It would be possible to create different covariances for different cloud temperatures. However, within the retrieval it would be challenging to know which one to use, unless we have some a priori information on the cloud altitude (as both ash and meteorological clouds will decrease the brightness temperature). There is potential to implement them using data from either a previous pixel or an alternative source but this would entail a lot of work to make a large change to the retrieval and is beyond the scope of this paper.

- Page 4, lines 24-26: You mention clouds above and below the ash cloud. What about clouds at the same altitude as the ash cloud? And what about the presence of ice in the ash cloud itself? The latter is known to be a challenge, see for example Rose et al. (1995), Durant et al. (2008), Kylling (2016). Please discuss.

  The authors agree with the referees remark regarding ice. It provides a large challenge and some discussion has now been added to the text. p.5 l.7 'The clear-sky covariance also encompasses scenes for which there is a thin meteorological cloud beneath the plume that does not alter the window channel temperature significantly, whilst there is no covariance matrix that is able to cope with a thick meteorological cloud above the ash plume, meaning retrievals in these scenes are still challenging. The covariance used in scenes where meteorological cloud is at the same altitude as the ash plume will depend upon the optical thickness of the cloud and the retrieved ash optical depth is expected to be an underestimate of the actual ash plume properties. Further challenges caused by the presence of ice in the ash plume due to the similarity in their spectral signatures are well known (Rose W. I. et al., 1995; Durant et al., 2008; Kylling, 2016). Some of their variability will have been captured in the covariance matrices. How-

ever, if the ash particles have become coated in ice, the optical properties are changed and the retrieval may underestimate the quantity of ash. Further work will look to better distinquishing the ash and ice cloud signitures. '

- Page 6, line 13: The ash cloud is assumed to be infinitely thin. Corradini et al. (2008) showed that ash cloud vertical extent have effect on the retrieved ash cloud optical properties. How realistic is the infinitely ash plume assumption and how does it affect your results? Is the error due to this assumption inluded in your error budget? If not, please make this clear in the manuscript.

  The authors are aware that the infinitely thin ash plume is a large assumption and will induce errors in the retrieval. However, for our retrieval method it must be assumed to be infinitely thin geometrically to allow for a full decoupling of the ash radiative transfer from that of the clear-sky radiative transfer. It is already stated in the manuscript that the error due to this is currently not taken into account in our error covariance matrix p.5 l.17 'It must be noted that there are further error components that are not considered within the current covariance matrices that may be addressed in future work. These are the errors associated with the modelling of the plume, such as; assuming a plane parallel atmosphere, assuming that there is no leakage of radiation from the edges of the plume, assuming that the plume has only a single layer, and assuming the ash particles to be spherical and have a log-normal size distribution of fixed spread. '

- Page 6, line 24: Pl is not used anywhere in the text. This line may be omitted.

  The text has been removed

- Page 6, line 28: Mention what ash size distribution is used and what parameters and values that describe it. Mention what ash type and refractive index that is used and include reference(s).

In response to this and other comments the paper now includes a more detailed description 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–$20\,\mu$m, to create the input for DISORT. Ignoring multiple reflections ...'

- Page 8, line 1: Please mention the wavenumber (wavelength) of the optical depths.

  This has been clarified to be at 550nm.

- Page 9, line 4: Please mention which longitudes are included in the "local" covariance matrix.

  This has been added to the text. p.9 l.13 'All examples consider a 'local'

error covariance matrix,* S_ϵ*, which is computed using spectra located at all longitudes within the latitude band,* $30°–60°$ *N, above the Icelandic plume region, ...'

- Page 9, line 11-13: I do not understand how this explains the decrease in temperature uncertainty. Please clarify. You may also possibly use the simplified model by Prata and Grant (2001) to explain the observed behaviour, see their Eqs. (2)-(5).

  A reference to Prata and Grant (2001) has been added to the text. p.9 l.24 'It is also known that discerning ash plumes from meteorological cloud is challenging when the temperature contrast with the surface is very small (Prata and Grant, 2001).'

- Page 10, line 4: Please specify the threshold value.

  This has been added to the text. p.11 l.13 '...but also only consider the retrieval a success if it converges within 10 iterations and the normalised cost is below a specified threshold (default is 2)...'

- Page 10, line 8: Please mention what the average retrieved surface temperature including standard deviation. How does it compare to ECMWF values for the area?

  As mentioned in response to the referees first comment, the authors do not believe that the quantities are directly comparable.

- Page 11-12, lines 2-8: Do the MODIS and IASI retrievals use the same ash type and size distributions? If yes, please state so. If not, please state how any differences affect the comparison results.

  Yes the retrievals do both use the same ash type and assumed distribution. This has been clarified in the text p13 l.22 'These properties are the same as those assumed in the IASI retrieval.'

- Page 12, line 8: What are the units of the number 2.6?

  The units have been confirmed as g cm^{-3}

- Page 12, line 12: Several MODIS pixels cover one IASI pixel. Please mention how the MODIS ash optical propertis vary across the IASI pixels. This variability may be included as vertical error bars in Fig. 6.

  The variability of the MODIS data across the IASI pixel, given as the standard deviation of the averaged values, has been added as error bars to Fig. 6. Please note that, due to updates in the algorithm that reduced the cost of some retrievals, there are additional points to the plot previously presented. The IASI retrieval error has also been added for completeness. Changes in the text: Fig 6. caption: 'Comparison of AOD at $11\ \mu$***m retrieved from IASI and MODIS during the Eyjafjallajköull eruption. The error bars show the associated IASI retrieval error and the standard deviation of the MODIS retrievals that were aggregated across the IASI pixel.'***

- Page 12, line 19: Please mention what the "imposed quality controls" are.

  The values have been included at p.14 l.12 'These measures ensure the output is sensible and realistic (e.g. the plume top altitude is not below the surface or the effective radius negative) and the normalised cost funtion must be below an imposed threshold of 2 for IASI and 5 for MODIS.'

- Page 12, line 27: Numbers for the "goodness" of the correlation may be obtained if fitting a straight line to the data.

  These values have been added. As above, note that the values have altered very slightly due to the new dataset. In text: p.14 l.17 'Reasonable correlation, $r = 0.47$***, is observed between the two instruments with an RMSE value of*** 0.66***. It is visually clear that there is a grouping of pixels where MODIS overestimates the value of AOD compared to IASI. These coincide with the***

higher MODIS cost values and largest pixel variability (shown as error bars in Fig. 6) at AOD > 1. Removing these pixels, the correlation is much improved to $r = 0.64$. This is especially true for lower values of AOD, where the RMSE reduces to 0.2 (for AOD < 1) and 0.17 (for AOD < 0.5). As the AOD increases, the spread of the data also increases with the tendency for MODIS to see a higher AOD than IASI. However, there is a time difference between the data points and therefore, the instruments may not be viewing the same part of the plume, despite attempts to minimise this. Hence, perfect agreement is not expected and the correlation seen is extremely encouraging.'

- Page 12, line 30: Eyjafjallajköull → Eyjafjallajökull.

  This has been corrected in the text.

- Page 14, lines 17-18: You state that "The retrieved effective size distribution from IASI measurements is consistent with the values from the aircraft measurements, although slightly smaller." Here you state that you retrieve the effective size distribution from IASI measurements. Is this really so? Is it not the effective radius you retrieve based on an assumed size distribution? Please clarify.

  The authors agree that this statement is misleading and it has been reworded to be more clear. p.16 l.13 ' The distribution of retrieved effective radius from IASI measurements is consistent with the values from the aircraft measurements, although slightly smaller. '

- Page 14, lines 15-20: When comparing effective radii, please provide numbers for the IASI effective radius. This you may obtain by fitting a curve to the histogram in Fig. 7 and thus obtain an estimate of the IASI effective radius.

  Fig. 7 is a histogram of retrieved effective radius. It is meant to demonstrate the variation of effective radius within the ash plume. If the referee would

like some representation of the effective radius of the entire plume then the mode of this distribution is a better statistic then forming the effective radius from a distributions of effective radii. This has been added to the table of values.

- Page 16, lines 23: What is implied by “The colocation for this scene is good”? Please quantify time and spatial differences.

  The information has been added: ‘The colocation for this scene is good (within 1.5 ***hrs and*** 50 ***km), with the CALIOP track directly crossing the retrieved IASI plume at latitudes above*** $55°$ ***N.’***

- Page 16, line 25: 10 $\rightarrow$ Fig. 10.

  This has been corrected in the text.

- Page 16, line 26: Please quantify “good agreement”.

  Further statistics have been added to the text. p.19 l.3 ‘...The outliers are reflected 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*** 11^{th} ***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,...'

- Page 16, line 30: Please beaware that the altitudes in Stohl et al. (2010) are derived from IASI and SEVIRI measurements using an inversion procedure. They only include the altitude of the fine ash that may be dispersed. Thus their use as a reference here is dubious. For the altitude of the plume above the volcanic vent the Arason et al. (2011) reference is maybe more appropriate.

  The authors take the referees point on board and have changed the reference.

- Page 17, Fig. 8: What is shown by the solid line in the Figure?

  It has been made clearer in the caption what each part of the figure illustrates. 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 22^{nd} ***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.'***

- Page 18, lines 14-15: This could be due to the ash cloud being above an optically thick low altitude cloud, case b in Fig. 2. If the below cloud is optically thick the retrieved surface temperature should represent that of the cloud and not the Earth's surface. Thus it would be interesting to know the retrieved surface temperatureds for these pixels and how they compare with the surface temperatures from for example ECMWF.

  The authors believe that under a thick cloud there should be little sensitivity to surface temperature and therefore the retrieved surface temperature (or effective radiating temperature) should be close to the a priori (ECMWF).

However, please see the authors comments to the first point regarding the 'surface temperature' and comparisons to ECMWF.

- Page 20, lines 16: You state "skewing towards slightly smaller particles due to viewing a larger area of the plume." However, I can not see that you have given evidence anywhere that the larger area is the reason. Yes, you speculate that this is the reason, but hard facts are needed to be able to firmly state this. Please clarify.

  The authors accept that this statement is not specific enough and have clarified that it is a potential cause. p.22 l.18 'Aircraft campaigns during the Eyjafjallajökull eruption confirm that the retrieved distribution of effective radii from IASI is in line with the aircraft measurements, skewing towards slightly smaller particles potentially due to viewing a larger area of the plume and therefore a slightly different distribution of the ash.'

Please also note the supplement to this comment:
http://www.atmos-meas-tech-discuss.net/amt-2016-143/amt-2016-143-AC2-supplement.pdf

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

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