EUMETSAT

MTG-FCI: ATBD for Volcanic Ash Product

Doc.No. : EUM/MTG/DOC/10/0560
Issue : v2
Date : 19 August 2011
WBS : MTG-834200

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Document Change Record

Issue / Revision	Remarks
v1 Draft	For internal review
v1C of 17 January 2011	First published version
v2 Draft of 19 August 2011	Updated following the recommendations of the System PDR Science Panel, including the results of a recent Science Study

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1 INTRODUCTION

1.1 Purpose of this Document

This document describes the algorithm theoretical basis for the Volcanic Ash (VOL) product, as it shall be derived from the Meteosat Third Generation Flexible Combined Imager (MTG-FCI).

1.2 Structure of this Document

Section 2 of this document provides a short overview over the MTG imaging instrument characteristics and the derived meteorological products, which will be referenced later in the text. This is followed by a detailed description of the underlying algorithm of the CRM product – its physical basis, the required input data, and a more detailed description of the product retrieval method. Section 4 describes possible future developments of the CRM algorithm

A full list of acronyms is provided in section 1.4, literature references are listed in the following section.

1.3 Applicable and Reference Documents

The following documents have been used to establish this document:

Doc ID	Title	Reference
[AD-1]	MTG End Users Requirements Document	EUM/MTG/SPE/07/0036
[AD-2]	MTG Products in the Level-2 Processing Facility	EUM/C/70/10/DOC/08
[AD-3]	MTG-FCI: ATBD for Radiative Transfer Model	EUM/MTG/DOC/10/0382
[AD-4]	MTG-FCI: ATBD for Cloud Mask and Cloud Analysis Product	EUM/MTG/DOC/10/0542
[RD-1]	Volcanic Ash Information Derived from Satellite Data (and references therein)	Contract EUM/CO/10/4600000775/MK
[RD-2]	Volcanic Ash Detection with MSG – Algorithm Theoretical Basis Document	EUM/MET/REP/07/0467

1.4 Acronyms and Definitions

The following table lists definitions for all acronyms used in this document.

Acronym	Full Name
AER	Aerosol Product
AMV	Atmospheric Motion Vectors
ASR	All Sky Radiance
ATBD	Algorithm Theoretical Basis Document
CMa	Cloud Mask
CRM	Clear Sky Reflectance Map
CT	Cloud Type
CTTH	Cloud Top Temperature and Height
FCI	Flexible Combined Imager
FCI-FDSS	FCI Full Disc Scanning Service
FCI-RSS	FCI Rapid Scanning Service
FDHSI	Full Disc High Spectral Resolution Imagery
GII	Global Instability Indices
HRFI	High Spatial Resolution Fast Imagery
HRV	High Resolution Visible Channel of SEVIRI
IR	Infrared
LUT	Lookup Table
MSG	Meteosat Second Generation
MTG	Meteosat Third Generation
NWP	Numerical Weather Prediction
OCA	Cloud Product (Optimal Cloud Analysis)
OLR	Outgoing Longwave Radiation
RTM	Radiative Transfer Model
RTTOV	Radiative Transfer for TOVS
SCE	Scene Identification
SAF	Satellite Application Facility
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SSD	Spatial Sampling Distance
TIROS	Television and Infrared Observation Satellite
TOVS	TIROS Operational Vertical Sounder
TOZ	Total Column Ozone
VIS	Visible (solar)
VOL	Volcanic Ash Product

2 OVERVIEW

2.1 Relevant Instrument Characteristics

The mission of the Meteosat Third Generation (MTG) System is to provide continuous high spatial, spectral and temporal resolution observations and geophysical parameters of the Earth / Atmopshere System derived from direct measurements of its emitted and reflected radiation using satellite based sensors from the geo-stationary orbit to continue and enhance the services offered by the Second Generation of the Meteosat System (MSG) and its main instrument SEVIRI.

The meteorological products described in this document will be extracted from the data of the Flexible Combined Imager (FCI) mission. The FCI is able to scan either the full disk in 16 channels every 10 minutes with a spatial sampling distance in the range 1 – 2 km (Full Disk High Spectral Resolution Imagery (FDHSI) in support of the Full Disk Scanning Service (FCI-FDSS)) or a quarter of the earth in 4 channels every 2.5 minutes with doubled resolution (High spatial Resolution Fast Imagery (HRFI) in support of the Rapid Scanning Service (FCI-RSS)).

FDHSI and HRFI scanning can be interleaved on a single satellite (e.g. when only one imaging satellite is operational in orbit) or conducted in parallel when 2 satellites are available in orbit. Table 1 provides an overview over the FCI spectral channels and their respective spatial resolution.

The FCI acquires the spectral channels simultaneously by scanning a detector array per spectral channel in an east/west direction to form a swath. The swaths are collected moving from south to north to form an image per spectral channel covering either the full disc coverage or the local area coverage within the respective repeat cycle duration. Radiance samples are created from the detector elements at specific spatial sample locations and are then rectified to a reference grid, before dissemination to the End Users as Level 1 datasets. Spectral channels may be sampled at more than one spatial sampling distance or radiometric resolution, where the spectral channel has to fulfil FDHSI and HRFI missions or present data over an extended radiometric measurement range for fire detection applications.

Table 1: Channel specification for the Flexible Combined Imager (FCI)

Spectral Channel	***Central Wavelength***, $\lambda 0$	***Spectral Width***, $\Delta\lambda 0$	***Spatial Sampling Distance (SSD)***
VIS 0.4	0.444 µm	0.060 µm	1.0 km
VIS 0.5	0.510 µm	0.040 µm	1.0 km
VIS 0.6	0.640 µm	0.050 µm	1.0 km 0.5 km [#1]
VIS 0.8	0.865 µm	0.050 µm	1.0 km
VIS 0.9	0.914 µm	0.020 µm	1.0 km
NIR 1.3	1.380 µm	0.030 µm	1.0 km
NIR 1.6	1.610 µm	0.050 µm	1.0 km
NIR 2.2	2.250 µm	0.050 µm	1.0 km 0.5 km [#1]
IR 3.8 (TIR)	3.800 µm	0.400 µm	2.0 km 1.0 km [#1]
WV 6.3	6.300 µm	1.000 µm	2.0 km
WV 7.3	7.350 µm	0.500 µm	2.0 km
IR 8.7 (TIR)	8.700 µm	0.400 µm	2.0 km
IR 9.7 (O_3)	9.660 µm	0.300 µm	2.0 km
IR 10.5 (TIR)	10.500 µm	0.700 µm	2.0 km 1.0 km [#1]
IR 12.3 (TIR)	12.300 µm	0.500 µm	2.0 km
IR 13.3 (CO_2)	13.300 µm	0.600 µm	2.0 km

[#1]: The spectral channels VIS 0.6, NIR 2.2, IR 3.8 and IR 10.5 are delivered in both FDHSI sampling and a HRFI sampling configurations.

2.2 Generated Products

The agreed list of MTG-FCI Level 2 products is detailed in [AD-2] and is repeated here for easy reference:

1. **SCE-CLA**:
   Scene Identification (cloudy, cloud free, dust, volcanic ash, fire) and a number of cloud products (cloud top height, phase)
2. **OCA**:
   Cloud Product (cloud top pressure and temperature, cloud top phase, cloud top effective particle size, cloud optical depth, cloud sub-pixel fraction)
3. **ASR**:
   All Sky Radiance (mean IR radiance on an n x n pixel grid, together with other statistical information, for different scenes)
4. **CRM**:
   Clear Sky Reflectance Map (VIS reflectance for all non-absorbing channels, accumulated over time)
5. **GII**:
   Global Instability Indices (a number of atmospheric instability indices and layer precipitable water contents)
6. **TOZ**:
   Total Column Ozone (technically retrieved within the GII product)
7. **AER**:
   Aerosol Product (asymmetry parameter, total column aerosol optical depth, refractive index, single scattering albedo, size distribution)
8. **AMV**:
   Atmospheric Motion Vectors (vector describing the displacement of clouds or water vapour features over three consecutive images, together with a vector height)
9. **OLR**:
   Outgoing Longwave Radiation (thermal radiation flux at the top of the atmosphere leaving the earth-atmosphere system)

The products will be derived from the spectral channel information provided by the FDHSI mission, on the resolution detailed in [AD-2].

An important tool for product extraction is a radiative transfer model (RTM), as described in [AD-3]. The IR model choice for the Level 2 product extraction is RTTOV, which is developed and maintained by the Satellite Application Facility on Numerical Weather Prediction (NWP-SAF). An RTM for solar channels is likely to be product specific and is yet to be fully determined.

This ATBD describes the algorithm of the Volcanic Ash (VOL) product, which in the above list is regarded as a sub-product of SCE-CLA. The retrieval process makes use of the results of the SCE and CLA product. The product will be derived over a certain processing area, defined as pixels lying within a great circle arc of pre-defined size around the sub-satellite point (typically 70°).

3 ALGORITHM DESCRIPTION

3.1 Physical Basis Overview

3.1.1 Ash Cloud Detection

Volcanic ash is a hazard to aircraft [RD-1], and for this reasons a volcanic ash satellite product can provide important information in this respect.

The problem of detecting volcanic clouds from satellites is really a problem of discrimination. Clouds absorb, emit and scatter radiation in the visible, infrared and microwave regions of the electromagnetic spectrum. At visible wavelengths, depending on the geometry of illumination (by the sun or using a laser light source) and the geometry of observation, clouds may appear bright or dark. This is true of clouds of water, ice, silicates (volcanic ash), wind-blown dust (desert dust), smoke (e.g. from a large forest fire) or any other naturally or anthropogenically generated cloud of particles. It is sometimes very clear that a particular cloud is meteorological in origin (for example, a cloud of water droplets or ice particles, or a mixed phase cloud), but the reverse is sometimes not so easy to assess.

By using objective analysis of daytime visible imagery alone, it has been very difficult to unambiguously discriminate ash clouds from other clouds and any visible method will fail at night anyways. This is the main reason why researchers have turned their attention to using infrared data [RD-1].

Volcanic ash plumes have been monitored with geostationary satellite images since the late 1970s. Commonly used is the "split-window" technique, for ash cloud detection also called "reverse absorption" technique. This technique uses the fact that the absorption of clouds (ice and water) is higher in channel IR12.3 than in IR10.5, but vice versa for ash plumes (see Figure 1).

However the split window method has still some deficiencies:

- Opaque ash clouds are still hard to distinguish from ice or water clouds, and ash clouds are often opaque within the first few hours of the eruption
- Ice embedded in the eruption cloud may obscure the ash signal
- In moist atmospheres (tropics) low level ash clouds may be masked by water vapour absorption effects.
- Semi-transparent clouds may give similar signals in the split-window as ash clouds

Concerning MTG-FCI, additional channel information can support and improve the "split-window" technique. For example some constituents of the ash clouds such as sulfur dioxide (SO_2) or sulfates can be detected in addition by channels in the 3.8, 7.3 and 8.7 µm bands on-board MTG-FCI.

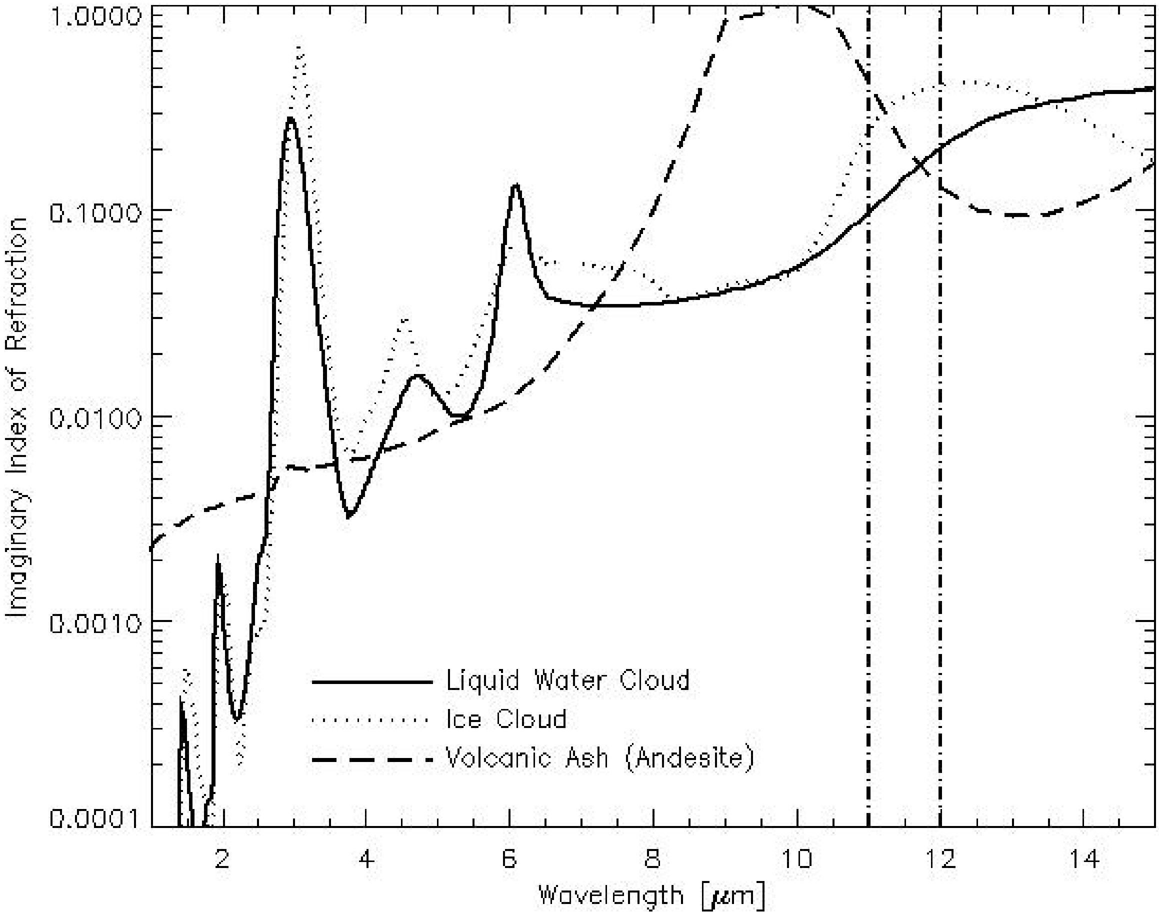

Figure 1: Imaginary index of refraction of ash, water and ice clouds

3.1.2 Retrieval of ash cloud particle size, optical thickness and mass loading

Satellite-borne infrared radiometers are used to measure atmospheric radiation in narrow wavelength bands, collecting energy from all components of the scene within the field of view of the instrument. In general terms, it is possible to solve the radiative transfer equation, governing the measurements over volcanic ash clouds.

In order to isolate the important factors affecting the radiative transfer (RT) inside an ash cloud, a heuristic model with the following (simplifying) assumptions can be used:

- the atmosphere below the cloud layer is assumed to be totally transparent: $L_a=0$
- the earth's surface below the cloud is assumed to be a black-body: $L_s=L_B[T_s]$
- the cloud consists of homogeneous particles at a single temperature, T_c
- the scene is observed under a specific satellite viewing angle

L_a is here the radiance emitted by the atmosphere, L_s the radiance emitted by the surface having temperature T_s, L_B is the associated blackbody radiance according to Planck's Law.

A dedicated Radiative Transfer Model (RTM) is used to calculate Lookup Tables (LUTs) which provide as result the ash cloud optical depth τ and the effective ash particle radius r for a given observation. This modelling task must be an offline activity, i.e. the LUTs must be available for the actual operational VOL processing. The necessary RTM is thus not described in this document.

A further result of the VOL processing is the total ash mass loading, expressed in kg m^{-2}, which is related to optical depth and particle radius according to:

$$M = \frac{4\pi}{3}\delta\, z \int_0^\infty r^3\; n(r)\, dr \qquad \textbf{(1)}$$

where δ is the density of the ash (a fixed value is assumed for δ), z is the geometrical thickness of the cloud, r is the ash particle radius, and n(r) is the number of particles per unit volume.

The number of particles per unit volume n(r) is related to the optical depth according to

$$\tau = \pi\, z \int_0^\infty r^2\; Q_{ext}(r,\lambda)\; n(r)\, dr \qquad \textbf{(2)}$$

where Q_{ext} is the extinction efficiency, and λ is the wavelength.

Figure 2 in section 3.5.2.4 shows curves generated from such a Radiative Transfer Model illustrating the effects of particle radius and optical depth (infrared opacity) on the brightness temperatures and their difference.

In summary, the generated LUTs provide τ and r for a set of measured brightness temperatures in IR 10.5 and IR 12.3, surface and ash cloud temperatures, and viewing angles.

3.2 Assumptions and Limitations

The current volcanic ash detection algorithm is able to detect volcanic ash clouds with a minimum of false classifications at daytime. However, ash plume detection during night still remains challenging. In particular the fact that cloud edges and dust storms are showing similar results in the split window, i.e. brightness temperature difference of channels IR 12.3 and IR 10.5.

3.3 Algorithm Basis Overview

3.3.1 Ash cloud detection

The volcanic ash detection algorithm (VOL) is only applied to cloud contaminated pixels, as detected by the scenes analysis (SCE) [AD-3]. For the detected cloud pixels, the VOL algorithm uses the following criteria to check for ash cloud pixels [RD-2]:

- Reflectance ratio NIR1.6/VIS0.6 (day time and twilight only)
- Brightness temperature difference of channels IR 3.8 and IR 10.5 (night time and twilight only)
- Brightness temperature difference of channels IR 8.7 and IR 10.5
- Brightness temperature difference of channels IR 12.3 and IR 10.5

The main test for ash cloud detection is the brightness temperature difference test of channels IR 12.3 and IR 10.5. The brightness temperature difference test IR 12.3 – IR 10.5 may have similar differences for thin ice and water clouds as for ash clouds. For that reason, there is a need to filter out mis-classified clouds (typically ice clouds which are falsely detected as ash) during night, when the reflectance ratio test cannot be used. The thresholds will be different for day time, night time and twilight.

The thresholds are derived from forecast data and radiative transfer model output [AD-3], as well as from a database with static thresholds. Details are described in section 3.5.1.

3.3.2 Retrieval of Ash Cloud Particle Size, Optical Thickness and Mass Loading

In summary the solution process for determining mass loadings from two-channel IR sensors entails:

- Specify the ash cloud vertical extent
- Specify viewing geometry
- Determine boundary conditions at the cloud
- Specify the refractive indices of ash as a function of wavelength
- Specify the size distribution and particle shape
- Solve for cloud optical depth, particle size (radius) and mass

In this retrieval scheme the cloud optical depth and particle size (radius) have been pre-computed with a heuristic model and the values are stored in look-up tables (LUTs) for different surface temperatures, cloud top temperatures and satellite viewing angles.

Several parameters from the above list can be determined from the image data. These are:

(1) the clear-sky surface temperature T_s
(2) the cloud-top temperature T_c
(3) the ratio of extinction coefficients β that governs the magnitude of the "U"-shaped distribution of negative differences

A procedure for estimating these parameters from image data has been developed. A brief outline is given below.

1. T_s. is estimated by finding the maximum value of $T_{10.5}$ occurring in the data in the vicinity of the ash cloud.

2. T_c. is more difficult to estimate from the data, because the lowest value of $T_{10.5}$ may not necessarily correspond to the volcanic cloud. However, provided an area in

close proximity to the suspect cloud can be delineated it may be reasonable to assume that the lowest value is the cloud-top temperature.

3. Theoretical estimates of β suggest a value of around 0.7. A method for estimating β, T_s and T_c simultaneously has been developed by using the distribution of $T_{10.5}$ vs $T_{10.5} - T_{12.3}$. The distribution is first histogrammed (or binned) into intervals of 0.5 K in $T_{10.5}$. Then, the lowest values in each bin are found and a curve is generated giving the outline of the distribution. The curve is smoothed and fitted using a nonlinear least squares model. The model has three parameters: T_s, T_s - T_c and β that can be estimated from the fit.

The ash cloud vertical extent is computed according to section 3.5.2.1. The viewing geometry is calculated from the image pixel location. The refractive indices, the size distribution and particle shape have been incorporated in the radiative transfer model which generates the LUTs.

The information on Ts, Tc, the measured pair of brightness temperatures in IR 10.5 and IR 12.3 is then used to derive the cloud optical depth and particle size (radius). The final mass loading is obtained according to equation (eq.1).

3.4 Algorithm Input

3.4.1 Primary Sensor Data

For each pixel the reflectances (VIS and NIR) or brightness temperatures (IR) of MTG-FCI channels VIS0.6, NIR1.6, IR3.8, IR8.7, IR10.5, and IR12.3 must be available. The pixel resolution is 2 km for all IR channels. For channels VIS0.6 and NIR1.6 the original pixel resolution needs to be averaged to the same 2 km resolution.

3.4.2 Ancillary Dynamic Data

The Scenes Analysis Product (SCE) needs to be available for the VOL processing. The scenes type (Stype) is used to determine the cloud contaminated pixels which are needed to separate the cloudy pixels from the volcanic ash pixels. Pixels with a scenes type “cloudy” are included in the VOL processing, while pixels with scenes types “clear” and “unknown” are excluded from the VOL processing. The Cloud Analysis (CLA) product is used to provide the cloud top height. In addition, IR radiative transfer processing results [AD-3] are needed to generate the dynamic thresholds for the VOL processing.

3.4.3 Ancillary Static Data

The VOL processing needs a pixel-based land-sea-mask and surface type map as well as the pixel-based emissivity values for each of the infrared channels used in VOL. The pre-generated LUTs are also needed.

3.5 Detailed Description

3.5.1 Ash cloud detection

As described in section 3.3.1 the ash cloud detection is a simple thresholding technique with the following tests:

- Reflectance ratio NIR1.6/VIS0.6 (day time and twilight only)
- Brightness temperature difference of channels IR 3.8 and IR 10.5 (night time and twilight only)
- Brightness temperature difference of channels IR 8.7 and IR 10.5
- Brightness temperature difference of channels IR 12.3 and IR 10.5

The tests are only applied to cloud contaminated pixels, as detected by the scenes analysis (SCE) [AD-4].

3.5.1.1 Description of the Threshold Tests

The solar zenith angle is checked for day (solar zenith angle < 80°), night (solar zenith angle > 90°) or twilight (angle between 80° and 90°) conditions in order to select the appropriate thresholds and tests. (Note that the exact values of the solar angle thresholds should be configurable). The algorithm itself is based on a simple threshold algorithm.

During daytime, a pixel is identified as volcanic ash, if the following criteria are matched:

- The temperature difference IR8.7 - IR10.5 is larger than threshold1
- The temperature difference IR12.3 - IR10.5 is larger than threshold2
- The reflectance ratio NIR1.6 / VIS0.6 is larger than threshold3

During twilight, a pixel is identified as volcanic ash, if the following criteria are matched:

- The temperature difference IR8.7 - IR10.5 is larger than threshold1
- The temperature difference IR12.3 - IR10.5 is larger than threshold2
- The reflectance ratio NIR1.6 / VIS0.6 is larger than threshold4
- The temperature difference IR3.9 - IR10.8 is between threshold5 and threshold6

During night, a pixel is identified as volcanic ash, if the following criteria are matched:

- The temperature difference IR8.7 - IR10.5 is larger than threshold1
- The temperature difference IR12.3 - IR10.5 is larger than threshold2
- The temperature difference IR3.9 - IR10.5 is between threshold7 and threshold8

3.5.1.2 Derivation of the Thresholds

The thresholds used to perform the above described tests are derived as follows:

$$\text{Threshold1} = a_{1,1} + a_{2,1} * T_{PCS,8.7} + a_{3,1} * T_{PCS,10.5}$$
$$\text{Threshold2} = a_{1,2} + a_{2,2} * T_{PCS,1230} + a_{3,2} * T_{PCS,10.5}$$
$$\text{Threshold3} = a_{1,3}$$
$$\text{Threshold4} = a_{1,4}$$

$Threshold5 = a_{1,5} + a_{2,5} * T_{PCS,3.9} + a_{3,5} * T_{PCS,10.5}$
$Threshold6 = a_{1,6} + a_{2,6} * T_{PCS,3.9} + a_{3,6} * T_{PCS,10.5}$
$Threshold7 = a_{1,7} + a_{2,7} * T_{PCS,3.9} + a_{3,7} * T_{PCS,10.5}$
$Threshold8 = a_{1,8} + a_{2,8} * T_{PCS,3.9} + a_{3,8} * T_{PCS,10.5}$

with ($T_{PCS,chan}$) denoting the predicted clear sky brightness temperature in channel *chan* derived from the ECMWF forecast with the help of the RTTOV radiative transfer model [AD-3]. Typical values for the coefficients ($a_{i,j}$) for MSG-SEVIRI are listed in Table 2. The corresponding values for MTG-FCI will need to be established during commissioning and should therefore be configurable.

Threshold	$a_{1,x}$	$a_{2,x}$	$a_{3,x}$
Threshold1	3.0	1.0	-1.0
Threshold2	2.0	1.0	-1.0
Threshold3	1.3		
Threshold4	1.5		
Threshold5	4.0	1.0	-1.0
Threshold6	10.0	1.0	-1.0
Threshold7	0.0	1.0	-1.0
Threshold8	8.0	1.0	-1.0

Table 2: Coefficients to derive the VOL thresholds

3.5.2 Retrieval of Ash Cloud Particle Size, Optical Thickness and Mass Loading

In summary the solution process for determining mass loadings from two-channel IR sensors entails:

- Specify the ash cloud vertical extent
- Specify viewing geometry
- Determine boundary conditions at the cloud
- Specify the refractive indices of ash as a function of wavelength
- Specify the size distribution and particle shape
- Solve for cloud optical depth, particle size (radius) and mass

3.5.2.1 Specifing the Ash Cloud Vertical Extent

Studies of plume rise in stable stratified atmospheres [RD-1] suggest that to a reasonable approximation the vertical extent of a plume can be estimated from the cloud top height, which is provided by the CLA product [AD-4]. For a cloud top height zt_{op}, expressed in km, the plume thickness Δz is derived according to

$$\Delta z = 0.4 z_{top} \quad \textbf{(eq.3)}$$

Lidar measurements suggest that drifting volcanic plumes are no more than 1–3 km thick, but variable. The variability of cloud thickness along the plumes and the problem of not having simultaneous plume-top height and plume-base height data for each of the plumes, means that we cannot estimate plume thickness to any greater accuracy. The total mass can be calculated by multiplying (3.13) by the area of a pixel.

3.5.2.2 Specifing the Viewing Geometry

The viewing geometry (satellite viewing angle) is derived from the image data.

3.5.2.3 Determing the Boundary Conditions

The measured top-of-the-atmosphere brightness temperatures are corrected for water vapour before use in the retrieval scheme [RD-1]. A better correction could be done if independent measurements of the water vapour field were available (e.g. from ECMWF analysis of forecast fields). It is also necessary to be able to specify the temperature of the surface (T_s) below the ash cloud and the ash cloud top temperature (T_c), neither of which are known. These could also be estimated from independent data. However, in order to maintain the speed and ease of use of this retrieval scheme, T_s and T_c are estimated from the satellite image data. These temperatures are estimated as:

$$T_s \approx \max[T_{ij}]$$
$$T_c \approx \min[T_{ij}]$$

where T_{ij} are the scene temperatures in the 12.3 μm channel. Estimates are obtained for each image repeat cycle scene in the vicinity of the ash plume, where the exact definition of "vicinity" is TBD. There are obvious inadequacies in this approach and several improvements could be envisaged. For example, the maximum scene temperature may occur over clear land during the daytime, while the ash cloud may be over open ocean. A simple way to improve the estimate is to use a local search algorithm, by seeking maxima and minima in the vicinity of the ash cloud. Estimating T_c is equivalent to obtaining a cloud top height. Thus T_c could also be obtained by using an independent cloud top height and assuming a lapse rate (or using a measured lapse rate) to convert to a cloud top height. These improvements are left to a later update of the algorithm.

Once T_s and T_c are obtained, they are used to find the closest look-up-table (LUT), specified in certain temperature intervals for:

$$200K < T_c < 300K$$
$$225K < T_s < 305K$$

to look for the entry for the appropriate satellite viewing angle.

To account for some water vapour absorption in the estimate of T_s, 2 K is subtracted from the estimate and to account for cloud absorption (emissivity < 1), 2 K is added to T_c.

3.5.2.4 Solve for Cloud Optical Depth, Particle Size (Radius) and Mass

The values generated by the heuristic model are stored in look-up tables (LUTs) for surface and cloud top temperatures and satellite viewing angles.. The following figure shows the principle of how the values for particle size and optical thickness are retrieved

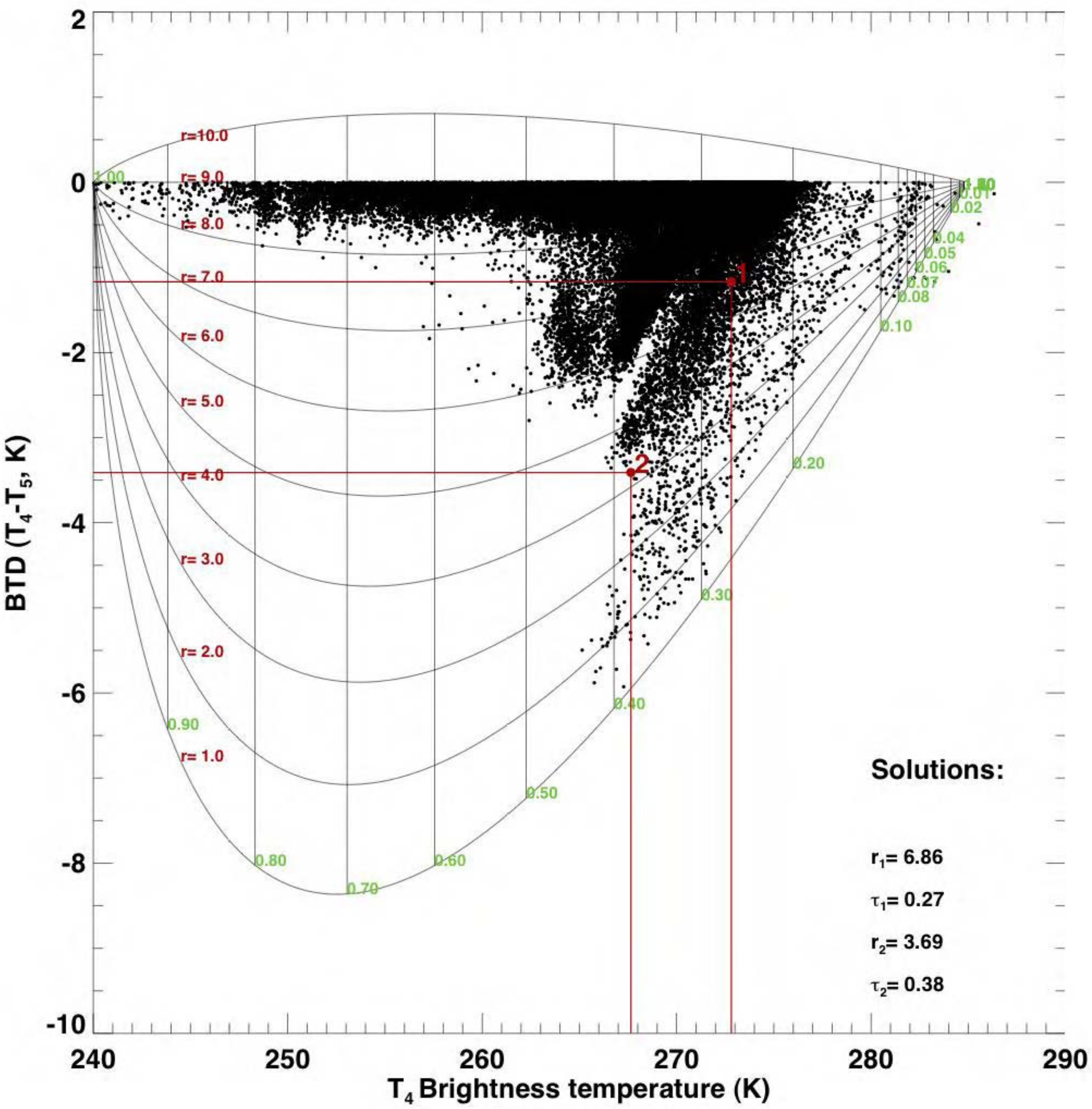

Figure 2: An example set of curves based on the heuristic model. In this case a simple parametric form for the variation of radius r with the parameter β has been developed. Solutions for two points are illustrated. In this figure T_4 stands for the brightness temperature of the 10.5 μm channel and T_5 stands for the brightness temperature of the 12.3 μm channel

Each curve corresponds to a different mean effective radius (indicated in red), and optical depth (indicated in green). The scatter of black points are actual observations, truncated with a value of BTD=0 K. By interpolating the curves in the data space ($T_{10.5}$, $\Delta T = T_{10.5}-T_{12.3}$), values of the mean effective radius and infrared optical depth can be determined. In this example solutions are shown for points 1 and 2. It can be seen that as ΔT approaches 0, multiple solutions for the optical depth are realised for a single value of the effective radius.

ΔT can approach 0 when either the ash clouds are very thick (then $T_{10.5}$ approaches T_c, the cloud-top temperature) or when the ash clouds are thin (then $T_{10.5}$ approaches T_s, the surface temperature).

The parameters are retrieved from the LUTs as follows:

In the ($T_{10.5}$, $T_{10.5}$ - $T_{12.3}$) plane there exist isolines of constant mean particle radius r . Each point on the isoline, r corresponds to particular values of the optical depth, τ. Lines connecting equal values of τ also exist. Given the measured values ($T_{10.5}$, $T_{12.3}$), the retrieval procedure requires us to find the 'best' values of (τ , r). Due to the temperature spacing in the LUTs, the final result is obtained by a linear 2-dimensional interpolation between the tabulated values.

3.6 Algorithm Output

The following data is output to the ash cloud detection and analysis algorithm:

- Ash cloud mask
- Ash mass loading
- Ash particle radius
- Ash optical thickness

4 FUTURE DEVELOPMENTS

4.1 Ash Cloud Detection

It is expected that improvements in the ash cloud detection will be achieved after implementing updates recommended by further studies. Also the new solar channels on-board of MTG-FCI may lead to an improved ash cloud detection during daytime.

Another improvement is foreseen by correcting for water vapour effects which is described below.

4.1.1 Correcting for Water Vapour Effects

One of the main problems with identifying ash in a cloud arises because often the ash is in a mixture with water molecules or ice particles. Water and ice clouds have $\beta > 1$ (see section 3.1.2), and therefore cause an opposite effect to that caused by ash clouds on the ΔT vs. $T_{10.5}$ diagram. The simple model can be examined further to correct for water vapour effects, or at least understand how these effects manifest themselves.

The proposed solution for this is as follows:

An empirical relation [RD-1] between the total precipitable water in the atmosphere and the brightness temperature difference ($T_{10.5}$ - $T_{12.3}$) is used to estimate the "water vapour effect"

$$\Delta T_{wv} = \exp [6T^* - b] \qquad \textbf{(eq.4)}$$

where $T^* = T_{10.5}=T_{max}$, and T_{max} is an arbitrary normalisation constant which is assigned a fixed value (e.g. 320 K). The free parameter b essentially determines the value of the water vapour effect on $T_{10.5}$ - $T_{12.3}$ at the maximum value of $T_{10.5}$. Hence b can be determined directly from the image data, allowing realistic flexibility on the size of the water vapour correction determined by this semi-empirical approach.

4.2 Ash Cloud Height Retrieval

Another future development is the derivation of the height of the volcanic ash plume together with the analysis of the optical properties (optical depth, particle radius), pending the outcome of a future Science Study.

4.3 SO_2 Retrieval

MTG-FCI has similar IR channels compared to MSG-SEVIRI. Therefore the following considerations are also applicable to MTG-FCI.

SO_2 has a strong absorption feature centred at 7.3 μm and a smaller one near to 8.6 μm that can be exploited to determine column abundance (**Figure 3**).

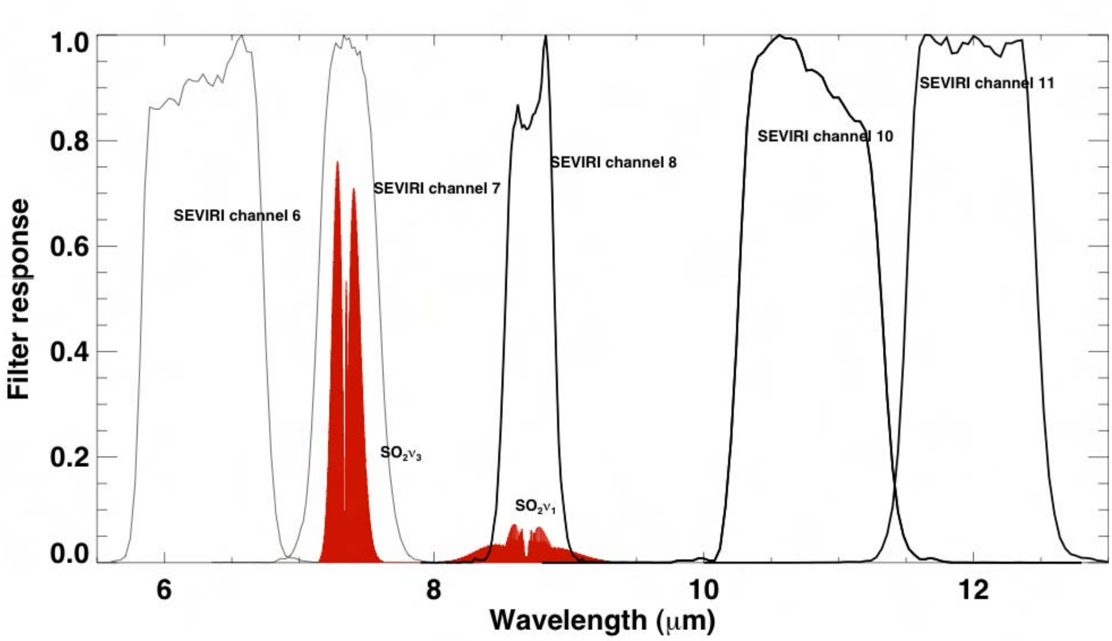

Figure 3: Positions of SEVIRI filter functions and vertical atmospheric absorption (on a relative scale).

The SO_2 signal in the IR 8.7 band is relatively weak so that saturation is unlikely, but there are constraints on using thermal data to determine SO_2 abundance. The main ones are: a need for thermal contrast, that is, the temperature of the absorbing layer needs to be different to the emitting (source) layer below, and the layer is largely free of other interfering gases and particles. Usually, the absorbing layer is colder. In addition the absorbing layer needs to be semi-transparent. If the layer becomes opaque then radiation from below will be completely absorbed and only emission from the layer will be observed. It is still possible to retrieve SO_2 in this case, but necessary to know the temperature of the layer. The SO_2 retrieval possibilities are also subject of a future Science Study.

5 GLOSSARY OF SYMBOLS

Variable Name	Meaning	Unit
L_a	Radiance contribution from the atmosphere	$mW/m^2/ster/cm^{-1}$
L_B	Blackbody radiance according to Planck's Law	$mW/m^2/ster/cm^{-1}$
L_s	Radiance emitted by the Earth's surface	$mW/m^2/ster/cm^{-1}$
M	Ash total mass loading in an atmospheric column	kg/m^2
n(r)	Number of particles of radius r per unit volume	$1/m^3$
Q_{ext}	Ash extinction coefficient	1/m
Stype	Identified scene type within the SCE processing	n/a
T	Brightness temperature	K
T_c	Cloud top temperature	K
T_s	Surface skin temperature	K
r	Ash particle radius	m
z	Geometric height	m
β	Ratio of absorption coefficients at two wavelengths	n/a
δ	Density	kg/m^3
λ	Wavelength	µm