Evaluation of Volcanic Cloud Top Height Retrievals Using Geostationary Satellite and Inversion Algorithm

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Abstract: *Volcanic cloud top height is an important parameter for ash dispersion models to enable a first order initialization of volcanic eruption parameters so that an accurate volcanic ash cloud dispersion pattern and eruption mass rate can be modeled. In this study, we evaluate the possible retrieval of volcanic cloud top height by exploiting the availability of satellite thermal band observations (brightness temperature, Tb) and radiative transfer simulations. Two different methods are evaluated, the first method uses only observed Tb from Geostationary satellite Geo-Kompsat 2A, and the second method is based on the inversion algorithm that uses the satellite Tb and a radiative transfer model. A case study of the recent Lewotobi eruption on 17th June 2025 is selected for the evaluation of these two methods. The time series of estimated height from these two methods are compared with the VAAC official forecast, and the assumption of each method is discussed.*

Keywords: Volcanic Ash, Cloud top height, Inversion modelling

1 Introduction

The Insular Southeast Asian region, especially Indonesia and the Philippines, is characterized with high volcanism which sometimes leads to disastrous eruptions and often eruptions large enough to have the potential to break flight engines down, halt air traffic, resulting in economic losses (Lechner et al., 2017). Furthermore, deep eruptions reaching the stratosphere can alter cirrus cloud properties and have a long-term impact on weather and climate (Lin et al., 2025; Mastin et al., 2009). The operational forecast agencies such as Volcanic Ash Advisory Center (VAAC) uses ash dispersion model (e.g. NAME: Jones et al., (2007)) to predict the ash clouds properties with time. The key source parameter for the dispersion model is the volcanic ash cloud top height. Highly accurate ash top height could simulate ash clouds to appropriate levels of the atmosphere, possibly generating a better forecast (Zidikheri et al., 2018).

The ash top height can be measured either from ground (Gasteiger et al., 2011), or airborne (Schumann et al., 2011), or space instruments e.g. (Lucas, 2023). Because of limited spatial and temporal coverage of ground and airborne instruments, satellite instruments in geostationary orbits (e.g. Himawari-8/9, GEO-KOMPSAT-2A (hereafter, GK2A)), which have the advantage of providing continuous observations at a higher spatial and temporal scale, are therefore used in this study.

There are several methods to estimate the height of the ash top from satellite measurements. The traditional method is to use a temperature profile either from radiosonde or from the Numerical Weather Prediction (NWP) model to identify the height level where the profile temperature closely matches with the satellite cloud top temperature (Lee et al., 2014). This method assumes the volcanic cloud is opaque ($\epsilon \approx 1$) and attains thermal equilibrium (Prata and Grant, 2001). However, real volcanic clouds could be made of multiple layers, semi-transparent and optically thin ($\epsilon < 1$). These assumptions and methods will be discussed further in the next section. Under such conditions, cloud top height can be retrieved by the optimal estimation method described by Rodgers (1976) and well adopted by Francis et al. (2012), Prata et al. (2022), and Mangla et al. (2025). However, this latter approach requires prior knowledge of atmosphere including clear-sky, meteorological cloud and ash cloud properties. Other methods such as parallax method (Nelson et al., 2013), wind correlation method (Tupper et al., 2004) also exist to estimate the ash top height, but these methods will not be discussed here.

On 17th June, a deep eruption occurs on Mount Lewotobi, an active volcano located at the Indonesian Island of Flores, in the East Nusa Tenggara Province (shown in Figure 1). The intensity of eruption was significantly high enough to halt air traffic in its neighboring airports (Bennis and Sennert, 2025). The main aim of the paper is to retrieve the top height of Lewotobi ash clouds with two different algorithms using GK2A satellite data. Section 2 describes the pre-processing of satellite dataset, the theoretical background of the two algorithms, and the methodology. Section 3 presents the results and discussion, followed by the conclusion in Section 4.

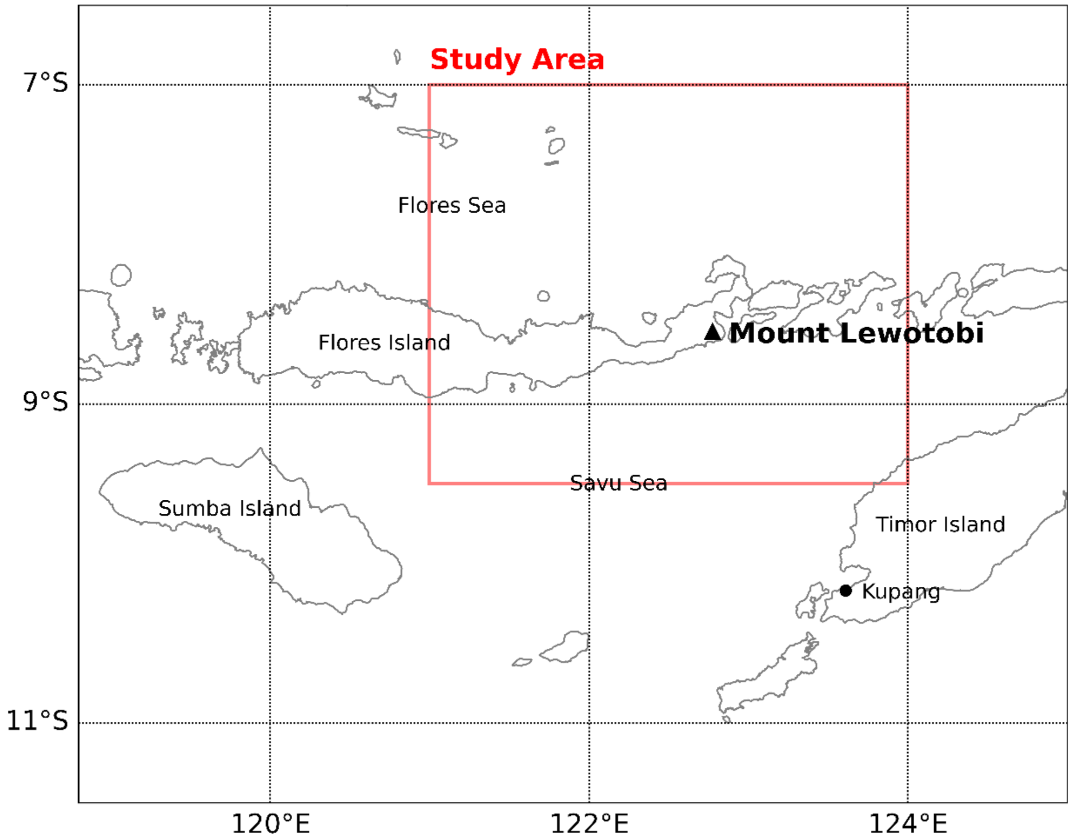

Figure 1: Location of Mount Lewotobi and its Geographic Surroundings

2 Data and Methods

2.1 GEO-KOMPSAT 2A

GK2A is a Korean geostationary satellite, located at 128.2°E, which serves to monitor the atmosphere over Asia-Pacific (mainly Korea, Japan, China, Southeast Asia including Indonesia and the Philippines) since its inception in December 2018 (Kim et al., 2021). Onboard the satellite, the GK2A Advanced Meteorological Instrument (AMI) consists of 16 channels which correspond closely to Himawari-8's Advanced Himawari Imager (AHI). Of interest to this study are the six infrared channels 11 through 16, which are useful for volcanic ash cloud monitoring both in day and nighttime. The AMI data offers high temporal resolution of 10 minutes. On the other hand, its spatial resolution is around 0.025° close to the equator (which is this study's region of interest).

For this data, level 1b data of AMI is utilized. In the provided NetCDF file, accessible through the Korean National Meteorological Satellite Center (NMSC portal), only the image pixel values are provided with *image_x* and *image_y* being its dimensions. These are the pre-georeferenced image-dependent variables. Additionally, these level 1b data of AMI is presented at its full pre-processed resolutions (around 0.025° in this study's region of interest). This higher resolution is useful for the detection of volcanic ash which usually is sensitive to the volcanic ash cloud's limited spatial extent, as will be demonstrated in this study. Since level 1b data of the AMI consists of only image-dependent variables, some minimal processing is needed such that the data can be useful for this study's purposes. From the provided dimensions variables, the brightness temperature, latitude, and longitude information needs to be extracted. This processing is done by using the sample code and conversion tables provided in the NMSC website, files titled *"20190516_sample_code2"* and *"20190415_GK-2A_AMI_Conversion_Table v3.0"* respectively.

Furthermore, since the explicit satellite geometry for every pixel, which is needed for the RTTOV radiative transfer forward model calculation (explained in next section), is not provided directly by the publisher of the data, these variables need to be calculated. For the sake of reproducibility of result, the processing of satellite geometric variables is explicated in this paragraph. Python library *'pymap3d'* is used to calculate the satellite geometry. First, the *sc_position center pixel* value from *sc_position* which is in an Earth-Centred Earth Fixed (ECEF) coordinate system is converted to a geodetic coordinate system. Using the geodetic latitude, longitude and elevation of the satellite and target pixel (which is obtained by processing using the sample code and conversion tables), *geodetic2aer* is calculated with the target pixel being the *"observer"* coordinate in the function (this is how satellite angles are defined). Additionally for the solar geometry, which is also needed for the forward model, an identical procedure is applied. The *sun_position_ecef* in *sun_position* is converted to geodetic coordinates, then the *geodetic2aer* is calculated for every target pixel. After processing, the AMI data now consists of brightness temperatures of its infrared channels, latitude and longitude, satellite geometries, and solar geometries.

Besides the AMI data, for evaluation and validation of this study, two official data are used: ground observations published by Center of Volcanology and Geological Disaster Mitigation of Indonesia (PVMBG) which is collected and archived by Smithsonian Volcanism Program in Bennis, K. L., S. Sennert (2025) and Volcanic Ash Advisory (VAA) published and available from VAAC Darwin. The latter, which serves as aviation warnings to the presence of volcanic ash in the atmosphere, is more accurate and precise than the former and therefore are more useful for evaluation and validation purposes.

2.2 Methodology

As mentioned in the introduction two methods to retrieve volcanic ash top height are used in the present study: direct measurement using temperature profile and radiative transfer inversion algorithm. The first method directly compares the brightness temperature of an (ash) pixel of one infrared channel, chosen to be channel 14 of the AMI centered on 11.212 µm, with the temperature profile (segment corresponding to either troposphere or stratosphere, determined a priori) of the atmosphere, given by ERA-5 reanalysis datasets, available at 0.25° spatial resolution, and 37 model levels (Hersbach et al., 2020). The height at which the temperature of the atmosphere is closest to the brightness temperature of channel 14 of the AMI is taken to be the retrieved volcanic ash height. Only the maximum height which corresponds to minimum brightness temperature of a scene (for every time) is retrieved, as the higher brightness temperatures of the other pixels can equally be caused by a lower height and/or an optically thinner cloud.

This direct measurement using temperature profile method relies on several simplifying assumptions: 1.) volcanic ash cloud is in thermal equilibrium with the surrounding atmosphere 2.) emissivity of the volcanic ash cloud is close to unity or 1, 3.) volcanic ash cloud is optically perfectly thick (all radiation from the ground is blocked), 4.) transmissivity of the atmosphere between the top of the ash cloud and the satellite is close to unity or 1.

Furthermore, as the ERA-5 spatial and temporal resolution is lower than that of the AMI data, for the first method, the retrieval is done at the full resolution of the AMI data using the ERA-5 temperature profile at the closest temporal and spatial location. This is justified by the fact that the height-temperature curve does not vary too quickly both in time and location. This choice is more precise than using a standard atmosphere height-temperature curve, or as a previous study has done, using a regional seasonal average of the height-temperature curve (Lucas, 2023). However, if higher resolution atmospheric data is available it is possible to have matching resolutions between the observation data and atmospheric data, which may give a more precise retrieval but not necessarily a more accurate one.

The second method, retrieval by a radiative transfer inversion algorithm utilizes a radiative transfer model, RTTOV, which generates a look up table (LUT), which then is inverted to retrieve the volcanic ash cloud height. This method is detailed explained in Mangla et al. (2025), only briefly mentioned here. Input to the radiative transfer model RTTOV consists of two distinct sets of parameters: artificial set of possible volcanic ash parameters and the atmospheric profile, provided by ERA-5. The artificial set of possible volcanic eruption parameters include volcanic ash top height {1, 3, 5, 8, 10, 12, 15, 18, 21} km, volcanic ash geometric thickness {0.1, 0.6, 0.8, 1.2, 2, 4} km, and volcanic ash concentration {0.5, 0.8, 1, 2, 3, 4, 6} mg/m3. For each combination of these eruption parameters, for every satellite image pixel, and using the ERA-5 profile at that pixel's location, RTTOV will generate a set of simulated brightness temperatures for infrared channels 11-16 of AMI, centered at 8.592, 9.625, 10.403, 11.212, 12.364, and 13.31 μm. These simulated brightness temperatures for every combination of eruption parameters make up the LUT for every pixel. Figure 2 illustrates the flow diagram of forward simulation, and inversion modeling to retrieve ash eruption parameters.

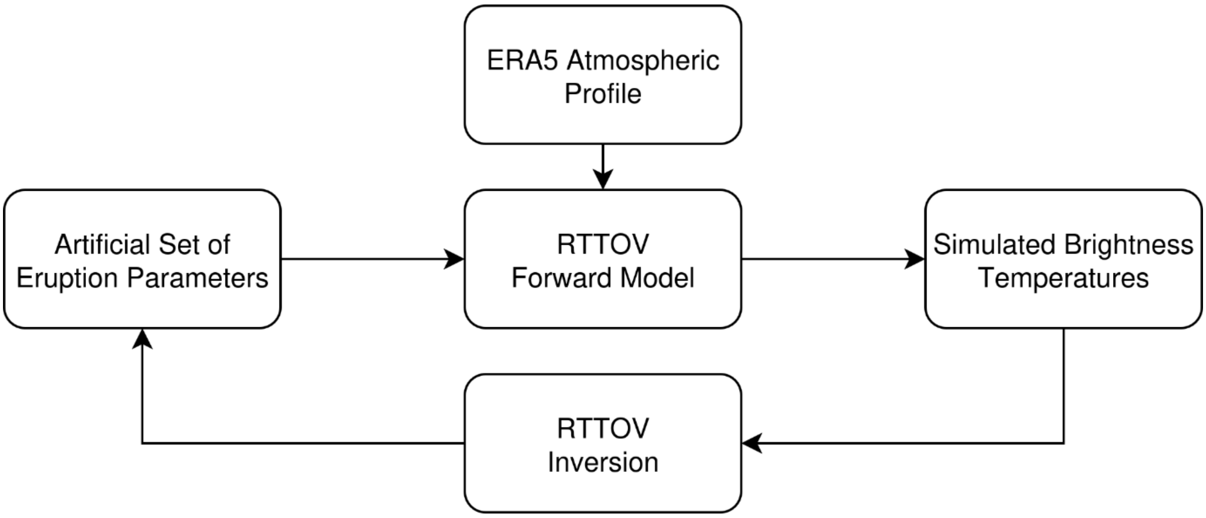

Figure 2: Flow diagram of the forward inverse modeling to retrieve ash eruption.

With these LUT, the Euclidean distances between the observed AMI brightness temperatures and their corresponding simulated brightness temperatures are calculated. The combination of eruption parameters that minimize the Euclidean distance between the observed and simulated values is taken to be the retrieved eruption parameters. In this study, the eruption parameter that is of concern is the volcanic ash cloud top height.

Unlike the first method of retrieval, the inversion method can only be done at the resolution of the ERA-5 due to reliance on atmospheric parameters (such as cloud fraction) that are more sensitive to spatial and temporal shifts than merely the temperature profile used in the first method. As a result, the retrieval resolution is limited to the low spatial resolution of 0.25°. This is the main limitation of this retrieval method.

Additionally, for the inversion method, the retrieval is only done for pixels identified to be non-opaque free ash by the brightness temperature difference (BTD) method. For every pixel, the difference between channels 13 and 14, bands centered around 10.403 and 11.212 µm, of AMI is calculated. This BTD differentiates ash, given by negative BTD, from water or ice clouds, given by positive BTD. This differentiation relies on the differential absorption at 10.4 and 11.2 µm for silica in volcanic ash and water in clouds. For this specific eruption, a threshold of -0.5 K is selected, i.e. pixels with BTD < -0.5 K are classified as ash. This threshold is found to filter out water cloud pixels over Sumba Island, which is clearly unrelated to the eruption by virtue of their time and location. This method also filters out possible water and ice clouds generated due to emissions (steam or nucleating ash) from the eruption.

3. Results and Discussion Data and Methods

3.1 Height retrieved using temperature profile

The Lewotobi eruption begins around 10 UTC on 17th June, and the cloud starts dispersing towards westwards from the volcanic site. Figure 3 shows the brightness temperature plots at selected times, 10:00, 10:30, 11:00, 12:00 UTC. Through these snapshots, both the dispersion of ash, and the resulting decrease of brightness temperatures are evident. At 10:00 UTC the volcanic ash cloud is very thick and is concentrated at the eastern end of the Flores Island, just west of the volcano location, Lewotobi. At 10:30 UTC, we can see that the core of the volcanic ash still has a relatively cold brightness temperature, while the edges have spread and increased in brightness temperature. It is also observed that the dispersion direction is westwards, in agreement with the VAA report. At 11:00 and 12:00 UTC the volcanic ash cloud has spread further westward to the middle of Flores Island.

The retrieved maximum volcanic ash cloud top heights between 10:00 UTC to 12:00 UTC at 10 minutes interval, from the direct measurement using temperature profile are presented in table 1. Between 10:00 UTC to 10:40 UTC, the retrieved maximum height is 15.4 km. The VAA volcanic ash cloud top height values of 16.2 km are well within the uncertainty of the retrieval method. Hence, the retrieval agrees with the VAA. From 10:50 UTC onward, a decrease in the retrieved heights are observed, this is unlikely from an actual decrease in the physical heights of the volcanic ash. This decrease is attributed to the dispersion and therefore a decrease in the optical thickness of the volcanic clouds. As discussed in the methodology section, this decrease in optical thickness leads to an underestimation of the volcanic ash cloud top height. As the dispersion goes on with time, the effect becomes more pronounced. The direct measurement method relies on the assumption that the volcanic cloud is significantly optically thick. This means that the method is valid only close to the eruption, before the ash gets dispersed and/or deposited. Conversely, since the ash is realistically not perfectly thick, there are still radiation from the ground, which has a higher temperature, that is not blocked, which would increase the brightness temperature. In the troposphere this means that the retrieved height would be an underestimate of the true height. On the other hand, the lower than 1 emissivity and lower than 1 transmissivity would lower the brightness temperature, but this study has found that this latter effect is not as significant as the former. Therefore, the overall effect produces an underestimation of height in the troposphere and an overestimation of height in the stratosphere, which worsens as the ash gets dispersed and deposited over time.

Both the directly measured ash cloud top height and VAA differ from the officially reported ground observation of 11.7 km or 10 km above the summit at 9:45 UTC. Ground observation involves an estimation based on visual observation, therefore are expected to not be precise. Therefore the discrepancy of value is expected and not indicative of a problem with the retrievals. Furthermore, only the initial eruption at 09:45 UTC is significant enough to be observed through satellite, the eruptions around 14:00 UTC only appear to be a few evanescent pixels in the full resolution BTD plots using AMI, quickly dissipating, indistinguishable from noise.

Table 1: Ash top height retrieved during 10:00 to 12:00 UTC using the direct measurement method every 10 minutes interval.

Time (UTC)	Minimum Tb (K)	Maximum Height (km)	Location
10:00	197.86	15.4	8.55S, 122.71E
10:10	201.49	15.4	8.51S, 122.69E
10:20	201.40	15.4	8.49S, 122.65E
10:30	202.01	15.4	8.49S, 122.61E
10:40	203.02	15.4	8.48S, 122.56E
10:50	204.24	14.3	8.46S, 122.47E
11:00	205.72	14.3	8.44S, 122.41E
11:10	207.25	14.3	8.40S, 122.34E
11:20	208.77	14.3	8.38S, 122.29E
11:30	210.33	13.3	8.42S, 122.16E
11:40	211.95	13.3	8.42S, 122.10E
11:50	214.22	13.3	8.42S, 122.03E
12:00	217.27	12.5	8.42S, 121.99E

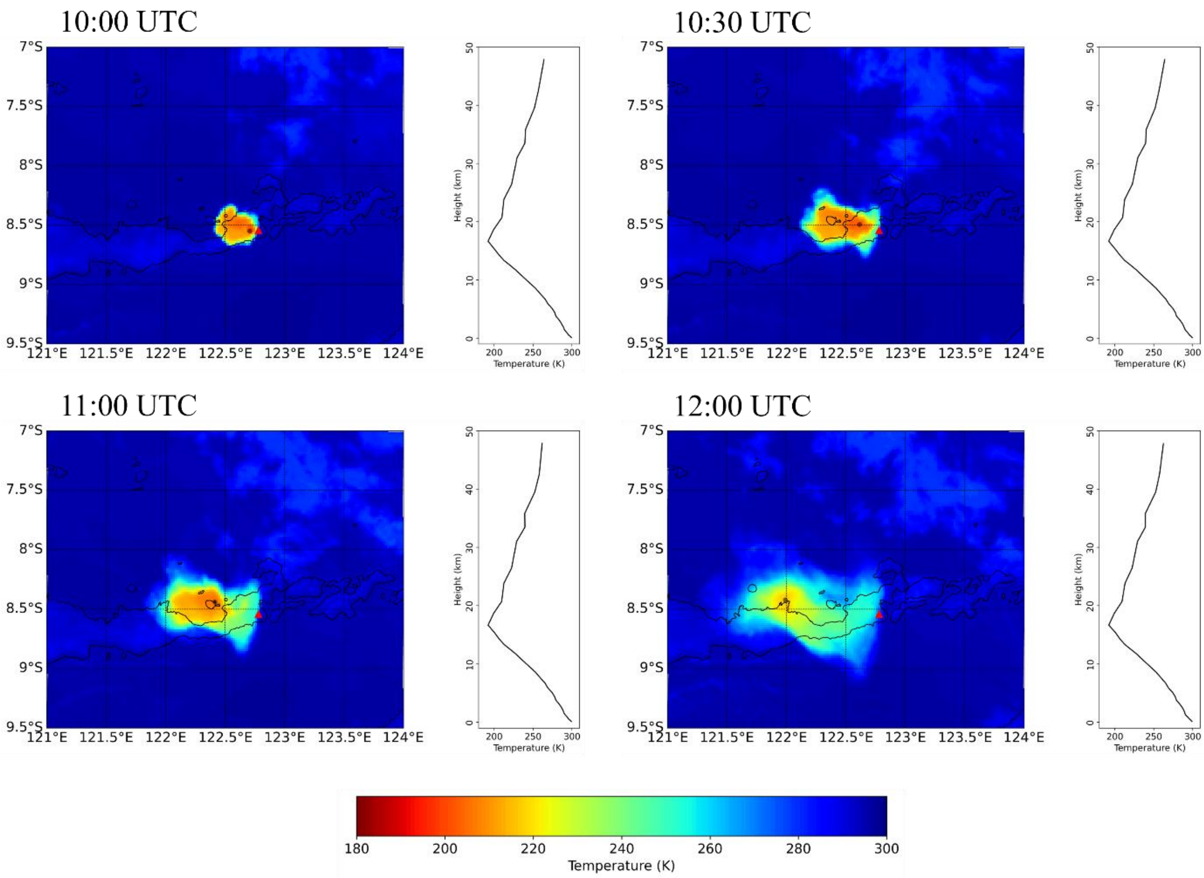

Figure 3: Retrieval by direct measurement using temperature profile plots, at 10:00 UTC (top left), 10:30 UTC (top right), 11:00 UTC (bottom left), and 12:00 UTC (bottom right). Pixel with lowest brightness temperature is marked with a grey circle, Lewotobi location marked with a red triangle. To the right of every plot, ERA5 Temperature-Height curves at nearest time and location to the lowest brightness temperature pixels.

3.2 Height retrieved using Inversion algorithm

The retrieved volcanic ash cloud top heights from the inversion method, its minimum, mean, and maximum values for every scene between 10:00 to 21:00 UTC, are presented in table 2. At 10:00 UTC no ash pixel was detected, this could be due to the ash not occupying enough fractions of the pixels (due to the low resolution of the method) or exceedingly optically thick volcanic ash clouds (beyond the range of the method). By 12:00 UTC, two patches of ash cloud emerge (refer to Figure 4), a westward moving and a southward moving one. Roughly 2 hours after the eruption, only 4 pixels were detected in the retrieval with a mean height of 9 km, a maximum of 10 km and a minimum of 8km. These particular pixels may not contain the ash with the actual highest volcanic cloud ash top height. In fact, between 10:00 to 14:00 UTC, the lack of number of pixels (statistically insufficient) imply that the maximum values of the retrieval may not reflect the actual physical values. At 14:00, the volcanic ash cloud has spread to a large enough spatial extent such that the actual volcanic ash cloud top is captured in the retrieval. This yields a retrieved maximum height of 18 km. While the mean value is at 10.6 km. The VAA value which is meant as an upper limit (due to its function as an aviation safety advisory) interestingly gives a lower value than the retrieved maximum height. This discrepancy can be further studied. Also, at 14:00 the two ash cloud patches are clearly distinct enough, patches in the west moving westward (in the direction towards Komodo, Lombok, and Bali) and one in the Savu Sea moving southwards. Higher ash stays in the atmosphere longer as the lower ash gets deposited faster, resulting in an increase in the mean value from 14:00 to 15:00 UTC. However, there are still some lower lying ash shown by the minimum. More significantly, the maximum value remains at 18km from 14:00 UTC to 21:00 UTC. From 15:00 UTC onward, the retrieved mean heights stabilized at around 16 km, which agrees with the VAA values. Overall, the inversion method is shown to be useful, at least in this particular eruption, after the volcanic ash particles have dispersed to enough pixels.

Table 2: Estimated mean, minimum and maximum volcanic ash cloud height using inversion algorithm

Time (UTC)	Minimum Height (km)	Mean Height (km)	Maximum Height (km)
10:00	0	0	0
11:00	8	9	10
12:00	7	8.5	10
13:00	7	7.6	9
14:00	7	10.6	18
15:00	10	15.3	18
16:00	8	15.6	18
17:00	11	16.9	18
18:00	8	16.5	18
19:00	7	15	18
20:00	7	15.5	18
21:00	18	18	18

3.3 Validation with official forecast

As explained above, the direct measurement using temperature profile and radiative transfer inversion algorithm, are found to be largely complementary. The direct measurement which is valid for thick volcanic ash clouds is useful for times closer to the eruption (from immediately after), while the inversion which is limited by resolution is useful after the ash has dispersed enough and occupied more spatial area. Figure 5 plots the retrieval results of the two methods: together with the VAA volcanic ash cloud upper limit heights issued by VAAC Darwin and ground reported heights published by the PVMBG agency. These retrieval results from AMI of the GEO-KOMPSAT-2A satellite agree to a large extent with the official VAA which is mainly derived from another more commonly used Advanced Himawari Imager (AHI) of the geostationary satellite Himawari-8 together with dispersion models. This retrieval result proves the potential for AMI to supplement the existing methods which mainly utilize AHI.

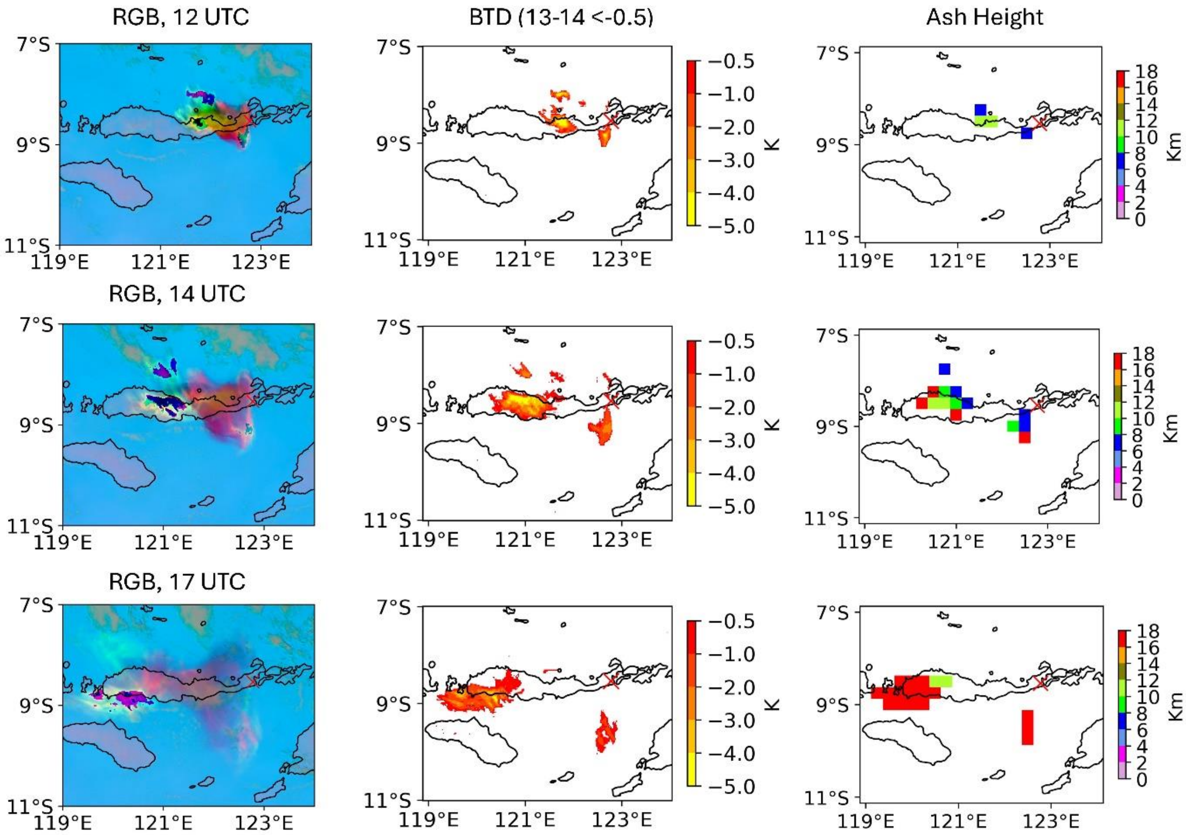

Figure 4: Volcanic ash false RGB plots at specified times, with red representing BTD, green representing signal associated with SO_2, and blue representing brightness temperature (left). Corresponding brightness temperature difference plots (middle). Retrieval results for volcanic ash heights by inversion algorithm (right).

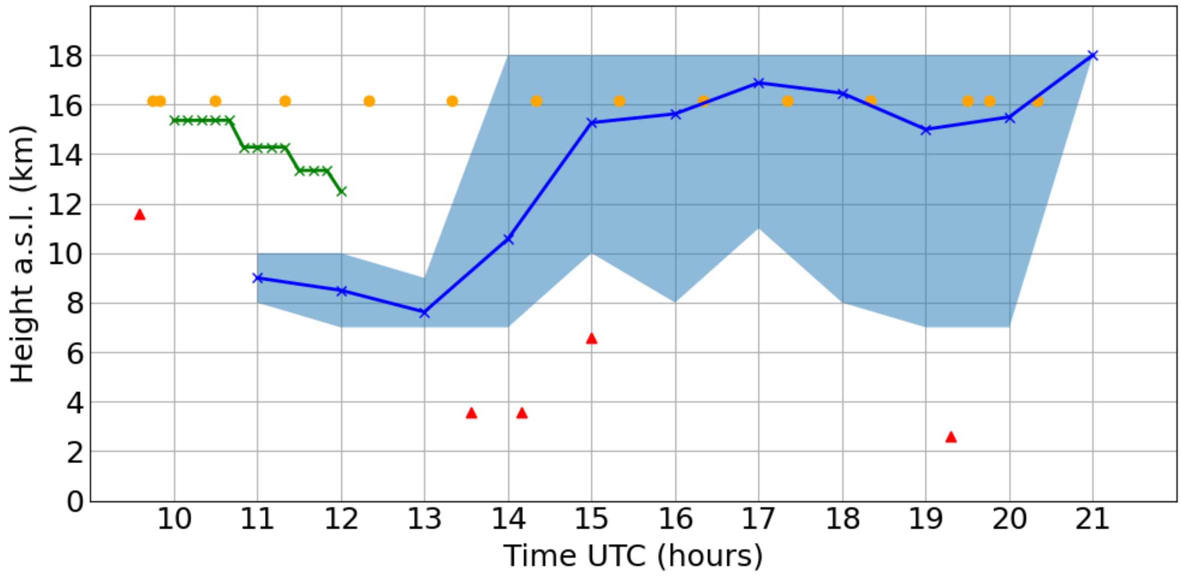

Figure 5: A graph showing temporal variation in the various volcanic ash height above sea level (a.s.l) values obtained through: (green) direct measurement result, the solid 'x' marked lines indicating retrieved top heights; (blue) radiative transfer inversion result, shaded area indicating maximum and minimum range of heights, solid 'x' marked lines indicating mean heights; (orange) Darwin volcanic ash advisory top heights (red) PVMBG reported volcanic eruption heights.

Conclusions and Perspectives

In summary, this paper has illustrated the complementary nature of the two methods of volcanic ash cloud top height retrieval: direct measurement from temperature profile and inversion of radiative transfer model. These two methods were applied to a Lewotobi volcanic eruption on 17th June 2025, using the Korean GEO-KOMPSAT-2A satellite. It was shown that direct measurement was more useful early on, right after the eruption, while the inversion was more useful later on after the ash has spread to a large enough spatial extent. This consideration would be beneficial if these two methods are to be integrated, together with a dispersion model, and incorporated into an operational system. Such an integration would incorporate the strengths of each component. Furthermore, this use of GK2A, when paired with another geostationary satellite like Himawari-8 opens up the possibility to other methods such as the parallax method, which is a more direct and purely geometrical method of retrieval. Parallax method using these two high temporal resolution satellites would possibly offer a more accurate retrieval with a very high frequency.

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