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Weather Radar Utilization for Monitoring Volcanic Activity to Support Flight Safety: A Case Study of Mount Marapi Eruption, West Sumatra, 22 December 2023

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Abstract

Volcanic ash can cause damage to aircraft engines and endanger flight safety. Weather radar has the potential to detect the height and direction of eruption cloud distribution, as well as the type of volcanic material. This research aims to close the technological gap in volcanic activity observation and eruption-height detection of volcanic eruptions using weather radar, based on a case study of the Mount Marapi eruption in West Sumatra on 22 December 2023. The method used in this research is to process radar data to produce weather radar products, specifically the CMAX (Column Maximum) product to determine the pattern of eruption activity and multi-VCUT (Vertical Cut) product to describe the eruption intensity, pattern characteristics, height, and distribution direction. The data used is the BMKG weather radar data from the Minangkabau Meteorological Station, West Sumatra. Before data processing, Clutter Identification and Radar Data Quality Control were carried out to reduce observation bias caused by ground-echo clutter.

The analysis results of the weather radar data show multiple episodes of continuous and sporadic eruption activity from Mount Marapi during a single day of observation. These results are more detailed than the VONA (Volcano Observatory Notice for Aviation) reports based on visual observations. This provides an opportunity to develop a volcanic ash early-warning system that improves the accuracy and effectiveness of volcanic activity observations and enhances flight safety.

Keywords: *weather radar; volcanic activity; eruption height; volcanic ash; flight safety*

1. Introduction

The safety of air transport users is part of the efforts to protect the general public from non-military threats (Supriyadi, 2023). Flight safety is strongly influenced by many triggering factors, one of which is volcanic activity, both along flight routes and in airport operations around the volcano. The impact of volcanic activity can pose a threat to flight safety (Marzano et al., 2019; Prata, 2020; Syarifuddin et al., 2021) because the resulting volcanic ash can enter the engine and cause damage, potentially leading to engine failure (Marzano et al., 2013). One of the greatest dangers of volcanic eruptions is the volcanic material scattered during an eruption (Webley & Mastin, 2009). Volcanic material in the form of tephra or fine ash particles can remain in the atmosphere for a long time and can travel thousands of kilometers (Hapsari et al., 2019). In the history of aviation, the first recorded flight safety threat due to volcanic ash was experienced by a Boeing 747-200 British Airways aircraft on the London-Auckland flight route when it crossed Indonesian airspace and was forced to make an emergency landing at Halim Perdana Kusuma Airport Jakarta during the eruption of Mount Galunggung on 24 June 1982 (Durant et al., 2010; Takebayashi et al., 2021). A similar incident was also experienced by KLM's Boeing 747-400 aircraft during the eruption of Mount Redoubt in Alaska on 15 December 1989 (Hirtl et al., 2020; Takebayashi et al., 2021). The high risk and impact of volcanic ash, particularly regarding flight safety, have increased the awareness of airport authorities and prompted them to take mitigation actions, such as suspending airport operations when volcanic ash is detected approaching the airport. This effort is carried out as a mitigation measure for the safety of air transportation users, such as temporarily closing the airport, cancelling flights, and diverting flight paths (Takebayashi et al., 2021).

The observation and analysis of volcanic eruption impacts, particularly the direction and spread of volcanic ash, serve as the basis for decision-making regarding the suspension of airport operations under the supervision of ICAO (International Civil Aviation Organization) an international organization focused on flight safety and setting operational standards for aviation (Gabrielsen et al., 2017). Many flight incidents occurred due to volcanic ash dispersal, which impacted airport operations and flight safety. This has prompted ICAO to build collaborations with volcanology institutions to monitor dispersal patterns and provide timely forecasts of the direction of volcanic ash spread (Webley & Mastin, 2009).

In the Indonesian regulatory framework, decision-making in force majeure situations related to the impact of volcanic ash on flight safety is guided by Circular Letter Number 15 of 2019 and the Decree of the Director General of Civil Aviation Number KP.153 of 2019 concerning Collaborative Decision Making (CDM) Procedures for Handling the Impact of Volcanic Ash on Flight Operations Using the Integrated Web Based Aeronautical Information System Handling (I-WISH) Media. Many parties play a role in this collaboration, such as the Directorate General of Civil Aviation, the Ministry of Transportation, which in daily reports will inform volcanic eruptions that have an impact on the temporary closure of airport operations as a flight safety reason. Meanwhile, PVMBG as the Center for Volcanology and Geological Disaster Mitigation plays a role in providing eruption information in the form of VONA reports from direct visual observations at local observatories. Volcanic activity is observed directly or with tools such as binoculars or CCTV. The information will be submitted to the nearest VAAC (Volcanic Ash Advisory Center) according to the area of responsibility (Marzano et al., 2016). The Indonesian airspace is included in Darwin VAAC monitoring.

Remote sensing technology can be used for area-suitability assessments (Supriyadi et al., 2019). Weather radar is one of these technologies and serves as a ground-based observation tool. As the name implies, weather radar is designed for hydrometeorological observations (Binetti et al., 2022; Sokol et al., 2021). However, it can also be used in volcanic activity monitoring (Marzano, 2011). In several studies, weather radar has been widely used to monitor volcanic activity (Vidal et al., 2017), such as determining the height of the eruption cloud and the mass of the eruption (Marzano et al., 2019; Montopoli et al., 2013), ash volume (Marzano et al., 2007), ash distribution (Maki et al., 2021b; Marzano et al., 2019; Syarifuddin et al., 2021) as well as the characteristics of the eruption material (Marzano et al., 2013). According to Donnadieu (2012), weather radar systems have been widely used to observe volcanic activity, which was first carried out during the eruption of Mount St. Helens around the 1980s. The eruption of Mount Eyjafjöll in Iceland from April to May 2010 was a devastating eruption that had a significant impact on air traffic in Europe as the resulting volcanic ash covered much of the airspace over mainland Europe resulting in the closure of Europe's largest airport for weeks (Marzano et al., 2011; Petersen, 2010). Until now, research on volcanic activity using weather radar systems still continues to be conducted on active volcanoes in the world.

When observing volcanic activity using weather radar, eruption patterns can be distinguished from convective cloud-precipitation patterns by adjusting radar reflectivity intensity based on the classification of volcanic ash material (tephra) in Table 1, adapted from the research of (Marzano et al., 2013) and Gematronik Weather Radar Systems Software Manual. The classification of tephra or volcanic material is divided into ash which is divided into fine ash (FA) and coarse ash (CA), lapilli which is divided into small lapilli (SL) and large lapilli (LL), and the form of blocks and bombs (BB). According to Hirtl et al. (2020), volcanic ash material, especially fine ash, has a particle size of <64 μm, which poses a significant hazard to flight safety. Although it does not directly cause damage to aircraft engines, high concentrations attached to turbine surfaces will cause blockages and affect aerodynamics in aircraft engines. In general, volcanic ash can cause various types of damage both inside and outside the aircraft. Volcanic ash particles can damage the exterior of the fuselage, and cause air filter blockages that can contaminate the air in the cabin.

Table 1 Classification of Volcanic Ash Material (Tephra) on Radar Intensity

Tephra	Particle type	Typical particle size	Radar Intensity Classification
Ash	FA	<64 µm	–12 to –13 dBz
	CA	64 – 532 µm	16 – 17 dBz
Lapilli	SL	0.532 – 2.56 mm	46 – 47 dBz
	LL	2.56 – 32 mm	63 – 64 dBz
Blocks	BB	>32 mm	not detected

Source: Modified from Marzano et al. (2013) and Software Manual Rainbow®5, Products & Algorithms, Gematronik Weather Radar Systems

In Indonesia, despite having the largest number of active volcanoes in the world, research related to volcanic activity by utilizing weather radar technology is still rare. Several previous studies have been conducted, such as that by Giammello et al. (2022), observing the volcanic activity of Mount Etna in Italy using S-Band Doppler weather radar to analyze the distribution of eruption pyroclastic material. The volcanic information is used to complete the VONA report, which is useful for aviation authorities. Another study was conducted by Marzano et al. (2019) on the observation of the eruption of Mount Etna on 23 November 2013 using X-Band and L-Band type weather radars with the volcanic ash radar retrieval (VARR) method. This method measures the height of the eruption cloud and the direction of volcanic ash distribution using three mass eruption rate (MER) techniques: the surface-flux approach (SFA), the mass-continuity approach (MCA), and the top-plume approach (TPA). This study aims to describe the ability of weather radar to detect eruption-cloud height and estimate the distribution of volcanic ash, and to compare these results with the VONA report from visual observations to improve volcanic information that is useful for flight safety.

This research uses a case study of the eruption of Mount Marapi in West Sumatra on 22 December 2023, which resulted in the closure of Minangkabau International Airport area based on NOTAM (Notice to Airmen) issued by the NOTAM Office with Number B2559/23-NOTAMN. According to the Directorate General of Civil Aviation of the Ministry of Transportation, the eruption caused the cancellation of 15 domestic and international flights and one flight returned to base (Kementerian Perhubungan Republik Indonesia, 2023). Based on PVMBG's visual observations in the VONA report for the 22 December 2023 event (Figure 1), one eruption activity was recorded at 05.19 UTC (12.19 Western Indonesian Time or WIB) which occurred continuously and was declared as "eruption and ash emission are continues" with the height of the eruption cloud not observed. This issue raises a big question for the author, why the eruption cloud was not observed during the eruption but caused the airport to be closed by the airport authority? To answer this question, the author offers a solution by using weather radar technology that has the potential to detect the height and direction of eruption cloud distribution and the type of volcanic material. Compared with visual observations in the VONA report, this technology is expected to help prevent and reduce recurring impacts and greater risks due to the dangers of volcanic ash for public health and flight safety.

2. Objectives

This study aims to close the technological gap in observing volcanic activity and detecting eruption heights using weather radar, based on a case study of the eruption of Mount Marapi in West Sumatra on December 22, 2023, and comparing the results with visual observations in the VONA report. The results of this research are expected to provide more quickly, accurately, and precisely information on the distribution of volcanic ash, to prevent and reduce the impact of volcanic ash hazards on flight safety and public health in future volcanic eruptions.

MARAPI 20231222/0519Z

(1)	VOLCANO OBSERVATORY NOTICE FOR AVIATION - VONA	
(2)	Issued	: 20231222/0519Z
(3)	Volcano	: Marapi (261140)
(4)	Current Aviation Colour Code :	ORANGE
(5)	Previous Aviation Colour Code :	orange
(6)	Source	: Marapi Volcano Observatory
(7)	Notice Number	: 2023MAR042
(8)	Valcano location	: S 0 deg 22 min 52 sec E 100 deg 28 min 23 sec
(9)	Area	: West Sumatra, Indonesia
(10)	Summit Elevation	: 9251 FT (2891 M)
(11)	Volcanic Activity Summary	: Ash-cloud is not observed.
(12)	Volcanic Cloud Height	: Ash-cloud is not observed.
(13)	Other Volcanic Cloud Information	: Ash-cloud is not observed.
(14)	Remarks	: Eruption and ash emission is continuing. Generated from Volcanic Eruption Notice (VEN).

Figure 1 VONA Report of Mount Marapi Eruption 22 December 2023

3. Materials and methods

This research used a descriptive analysis approach based on a case study of the eruption of Mount Marapi in West Sumatra on 22 December 2023 using weather radar. Mount Marapi is administratively located in Agam Regency, Tanah Datar, West Sumatra, at coordinates –0.381°N and 100.473°E, and has an altitude of 2891 meters above MSL (source: https://magma.esdm.go.id/v1). PVMBG began recording VONA reports of Mount Marapi eruptions in 2017 and continues to do so to the present., where in the past year the frequency of eruptions has increased. Several eruptions have even resulted in the closure of Minangkabau International Airport due to the volcanic ash reached that area.

Information on the eruption event was obtained from the VONA report which contains information on the time of the eruption, and the height and direction of movement of the eruption cloud, as a basis for determining the date of the events under study. The VONA report was obtained from the Center for Volcanology and Geological Disaster Mitigation (PVMBG) which can be accessed via the following link https://magma.esdm.go.id/v1/vona/. In this research, the VONA report was used as the basis for retrieving weather radar data by matching the report date to the event date. The eruption of this period caused the closure of Minangkabau International Airport operations due to the discovery of volcanic ash material on paper tests in the airport area.

In this study, the weather radar analysis uses BMKG weather radar observation data from Minangkabau Meteorological Station, West Sumatra. The Padang weather radar was built in 2007 with type C-Band radar. Generally, the weather radar operational standard uses VCP21 mode during normal weather conditions, but it can be operated using VCP31 mode for observations during clear weather conditions (air clear mode) with a time interval of 10 minutes and VCP11 for observations of potentially bad weather conditions with a time interval of 5 minutes. The technical specifications of Padang Weather Radar are presented in Figure 2.

LOCATION PROPERTY	
Latitude	0.786
Longitude	100.305
Altitude	24 m above MSL
Band Type	C-Band
Polarization	Single (Linear Horizontal)
Frequency	5,600 GHz
SYSTEM & DATA PROPERTY	
Beam Width	<1°
Pulse Repetition Frequency (PRF)	250 – 1200 Hz
Mode PRF	Single PRF
Range resolution (m) or spatial resolution	250 m
Scanning mode	VCP21
Total number of elevation angles for volumetric scan	9
Elevation angles (Observation order)	0.5° – 19.5°
Time resolution or required time for volumetric scan (min)	10 min (observation time for 6 min and standby time for 4 min)
Antenna speed	24°/s

Figure 2 The technical specifications of Padang Weather Radar

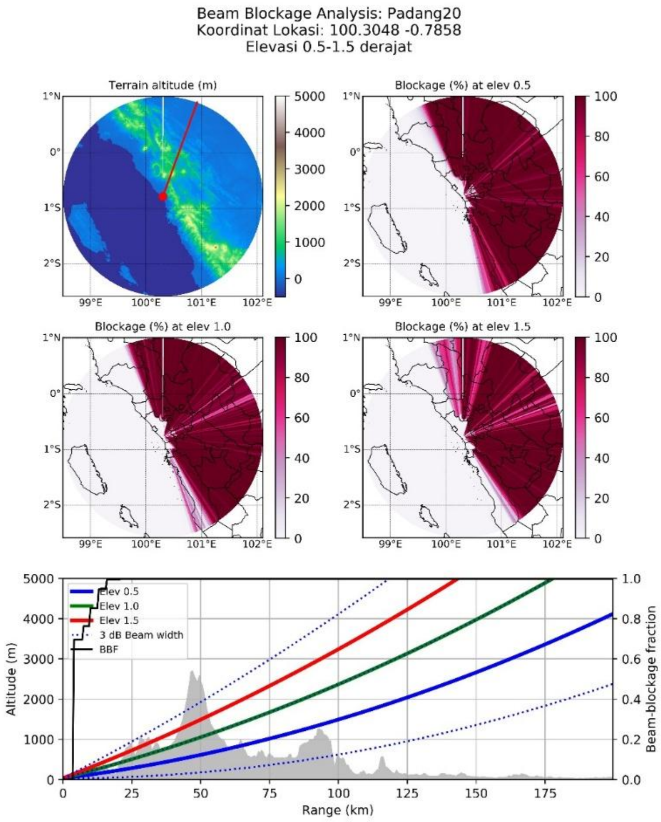

Figure 3 Beam Blockage Analysis Weather Radar Padang.

Measured from the Padang weather radar center, the location of Mount Marapi is about 47 km away, while the radar itself is located near Minangkabau International Airport area, approximately 1 km away. Technically, this distance is still optimal for observing volcanic activity and surrounding weather conditions near Mount Marapi. However, Mount Marapi is located along the Barisan Hill on the northeast side of the Padang weather radar. These geographical conditions may cause interference in weather-radar observations when identifying eruptive activity, in the form of ground-echo clutter, so it is necessary to carry out a filtering process and data quality control on Padang weather radar observations. The beam-blockage analysis of the Padang Weather Radar towards Mount Marapi is presented in Figure 3.

Weather radar data processing starts with clutter identification using fixed-character patterns to reduce misidentification of volcanic ash around the volcano area. In this research, quality control involved a filtering technique at the data-processing stage by identifying clutter characteristics from historical data to create a reference clutter-map correction. This process was carried out at the processing stage in the radar application to eliminate all echoes that have patterns according to the clutter map. This stage was essential process before analyzing the activity, pattern and height of volcanic ash. The next process involved processing the filtered data to produce the products needed to obtain information on the activity, pattern, and height of eruptions that occurred. The weather-radar data were processed using the Rainbow5 application version 5.49.13. The results will then be compared with the results of VONA observations.

Previous research was conducted by Maki et al. (2021a) on observations of the Sakurajima eruption in Japan using the Analytical Tools for Three-dimensional Weather Radar Data (ANT3D) analysis program to build 3D construction and visualisation of weather radar data. Whereas in this study, the information on the upright cross-section of the eruption cloud, material classification and ash distribution could be known directly using multi-VCUT and CMAX analyses.

The VCUT product parameters were modified by performing an upright-cut technique in eight wind directions as a multi-VCUT product to facilitate early detection of eruptive activity at the top of the volcano. By examining the reflectivity pattern in the multi-VCUT product, the pattern and dominance of the cut area over time reveal the movement of volcanic ash, especially 10-20 minutes after the first eruption. The upright profile of the multi-VCUT product also facilitates the identification of the erupted material and the height of the material blast. In this study, the reflectivity observed during volcanic activity correspond to the classification and characteristics of eruptive materials in Table 1.

The radar products used in the eruption event analysis in this study are Column Maximum Reflectivity (CMAX) and multi-VCUT (Vertical Cut/Cross Section) reflectivity. The CMAX product provides information on the maximum radar-observed reflectivity. The multi-VCUT is a derived reflectivity product that can provide detailed storm vertical profile information to determine the cell structure, storm core, and maximum reflectivity height. This product has high spatial resolution, providing vertical-profile reflectivity information that not only aids in classifying eruptive material but also in identifying eruptions that do not form ash clouds or plumes, such as emissions. This was consistent with Falconi & Marzano (2019), which stated that weather radar observations could provide a three-dimensional (3D) view of eruption cloud activity. This product could sometimes detect volcanic ash emissions from volcanic activity. In this study, the multi-VCUT product used a configuration designed to account for possible volcanic-ash movement in all directions. The configuration was carried out by considering eight wind directions to anticipate the spread of ash in all directions.

By combining the observations obtained from the two products (CMAX and multi-VCUT), a comprehensive analysis was then carried out to gain confidence in the eruption detection process that occurs. The two products complement each other in the eruption-identification stage. The multi-VCUT product not only aids eruption identification but also provides an overview of the direction of volcanic-ash particle movement. In data processing, the modification of cross-section parameters (VCUT) in the form of multi-VCUT was carried out by making slices in eight directions of the wind to observe the eruption pattern and movement of eruption material in more detail. Through the observation of multi-VCUT products, the dominant area of volcanic ash was observed from time to time. The dominant area of multi-VCUT detection becomes the initial information in determining the direction of volcanic ash distribution. This technique differs from previous research, in which VCUT was used solely to determine the maximum height of the eruption that occurred.

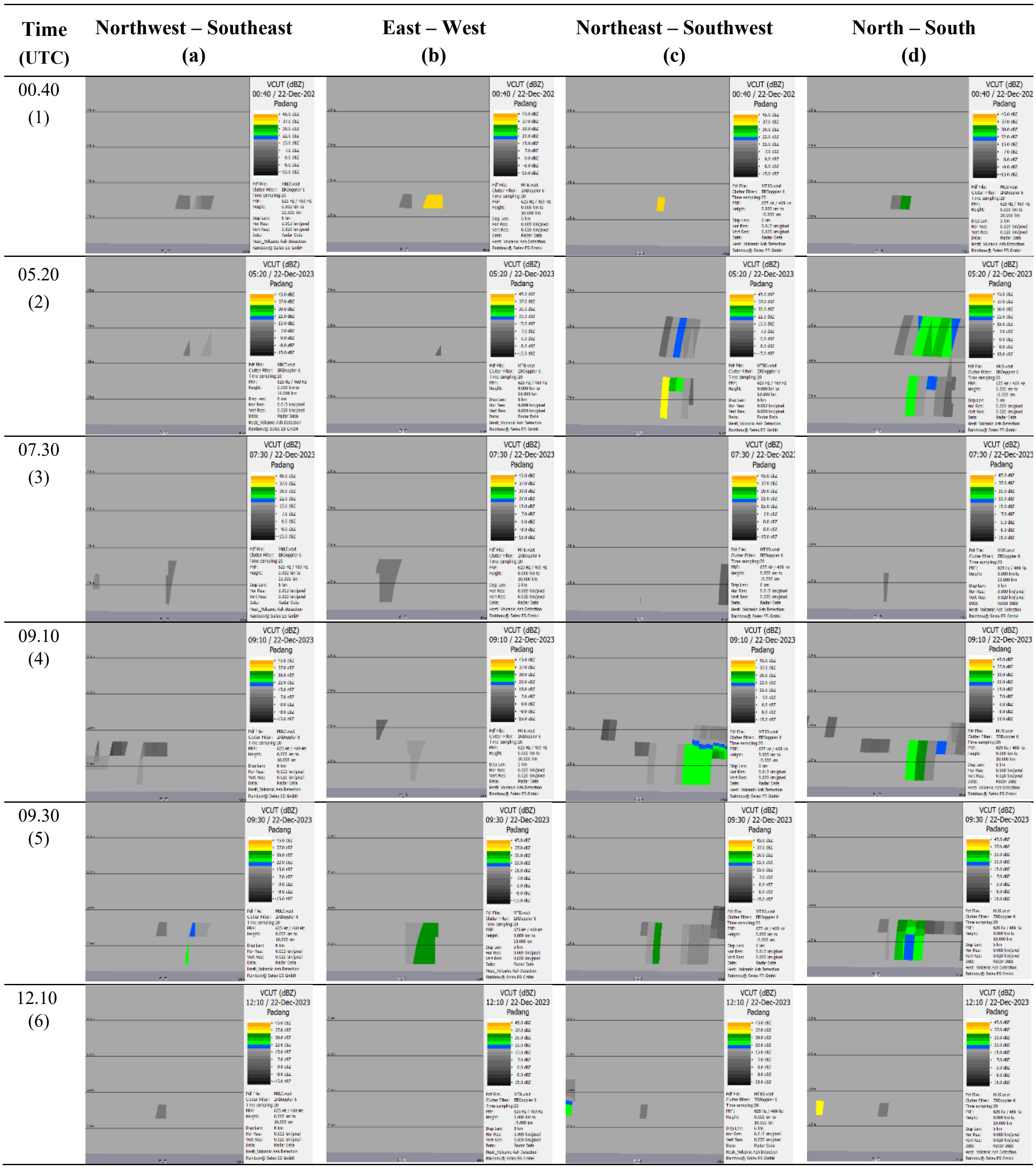

Figure 4 Multi-VCUT (Vertical Cut) products from Padang Weather Radar on 22 December 2023, showing six observation times: (1) 00.40 UTC, (2) 05.20 UTC, (3) 07.30 UTC, (4) 09.10 UTC, (5) 09.30 UTC, and (6) 12.10 UTC. For each time period, four directional vertical cross-sections are displayed: (a) Northwest–Southeast, (b) East–West, (c) Northeast–Southwest, and (d) North–South. The [+] symbol marks Mount Marapi's summit location. Color scale indicates radar reflectivity in dBz.

4. Results

Weather-radar data processing used 144 raw datasets from one day of radar observations on 22 December 2023. The initial analysis focused on the time surrounding the event reported in the VONA report at 05.19 UTC. The analysis of radar observation data showed that at around 05.20 UTC (12.20 WIB), Padang weather radar observation could detect volcanic activity. However, volcanic activity had already been detected earlier at 00.40 UTC (07.40 WIB), as shown in Figure 4, period 1. Based on the VCUT product, reflectivity was observed with the emission height reaching 3270 meters above MSL, with the movement of volcanic ash tending to the Southeast, shown in Figure 4(1a) which displays the Northwest–Southeast vertical cut. At 05.20 UTC (12.20 WIB), the volcanic-ash emission height reached 6670 meters above MSL with the movement of eruption material tending to the South-Southwest. These results were obtained from the analysis of multi-VCUT products, based on Figure 4(2c) and Figure 4(2d), which show the Northeast–Southwest and North–South vertical cuts respectively. The echo position appears on the right side of the mountain peak (marked by symbol [+]).

Other volcanic activity from Mount Marapi was detected by weather-radar observations at 07.30 UTC (14.30 WIB), with the emission height reaching 3,270 meters above MSL and volcanic ash movement tending to the Southeast, shown in Figure 4 at 07.30 UTC (panels 3a and 3d), which display the Northwest–Southeast and North–South vertical cuts respectively. Volcanic-ash emissions were again observed by the weather radar at 09.10 UTC (16.10 WIB) with volcanic-ash height reaching 4,570 meters above MSL, and at 09.30 UTC (16.30 WIB) with height reaching 3,270 meters above MSL. In both observations, the volcanic ash emission moved toward the Southwest, as shown in Figure 4 at 09.10 UTC and 09.30 UTC (panels 4c and 5c), which show the Northeast–Southwest vertical cuts. Weather radar observations at 12.20 UTC (19.20 WIB) showed that volcanic activity was again observed, with volcanic ash emission reaching 3,300 meters above MSL and moving toward the Southwest, as shown in Figure 4(6c) and 4(6d). Both the Northeast–Southwest cut (6c) and North–South cut (6d) confirm this directional movement. The analysis of Padang weather-radar observations showed that all volcanic activity of Mount Marapi throughout the day on 22 December 2023 could be observed by weather radar using the multi-VCUT product, as presented in Figure 4.

The determination of the dominant direction of volcanic-ash movement based on the multi-VCUT product was supported by the CMAX product, which illustrated the movement of volcanic ash in the same direction toward the South-Southwest, as shown in Figure 5 (all six time periods: 1–6). This was indicated by the reflectivity pattern at the top of Mount Marapi, which showed an eruption-particle type classified as Fine Ash (FA) with an intensity of <15 dBz as classified by Marzano et al. (2013) in Table 1, which leads South-Southwest towards Minangkabau International Airport. However, the Fine Ash (FA) particle type could not be visually observed because the particles were too small to be recorded in the VONA report.

In validating reflectivity in the CMAX and multi-VCUT products, eruption and precipitation patterns were distinguished by observing the reflectivity pattern on the upright cross-section of the VCUT product. In the upright cross section of precipitation, the rain cell structure has a growth process/ phase that begins with the appearance of light precipitation which then develops in the cell area as well as changes in the maximum reflectivity value, where the maximum reflectivity value in convective rain cells indicates the position of the cell core at an altitude of 3–7 km. The cell then decays, beginning with a decrease in maximum reflectivity and height until it dissipates completely. This upright cross-sectional structure is very different from the case of a volcanic eruption, where the reflectivity does not begin with a growth phase but immediately shows maximum values near the volcanic summit.

The reflectivity value in the event of volcanic ash emissions has a different pattern and structure from ground clutter, where the height and area of ground clutter usually have a fixed height that does not change, while volcanic-ash emissions display highly dynamic variations in both area and height. The eruption patterns observed in the CMAX and multi-VCUT products indicate that the eruptions were repeated and continuous in accordance with the VONA report which states eruption and emission are continuing and ash-cloud not observed at volcanic cloud height (Figure 1).

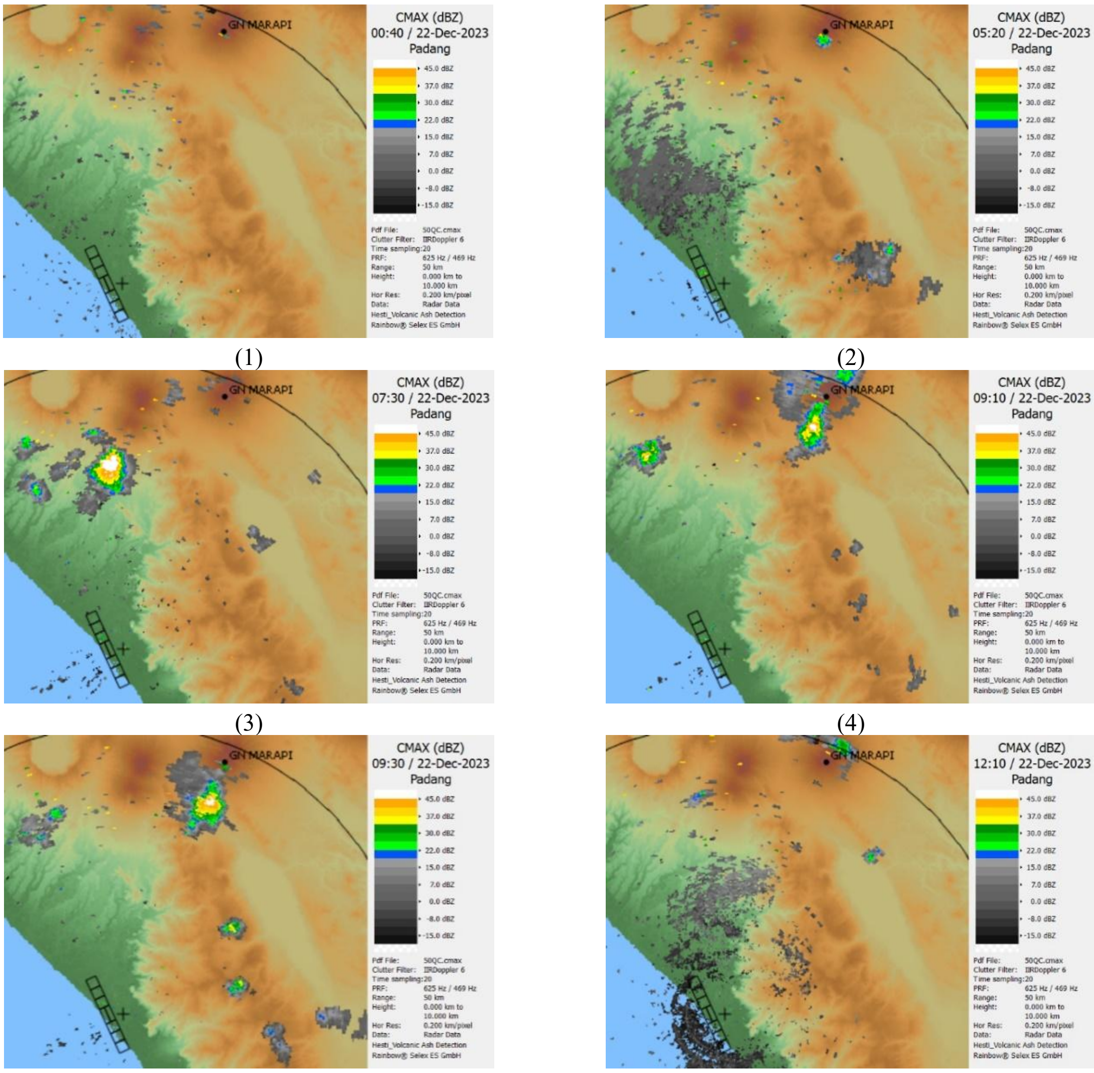

Figure 5 CMAX Products from Weather Radar Observations at 00.40 UTC (1), 05.20 UTC (2), 07.30 UTC (3), 09.10 UTC (4), 09.30 UTC (5), and 12.10 UTC (6).

Table 2 Volcanic Activity from VONA Reports and Weather Radar 22 December 2023

Date	Western Indonesian Time (WIB)	UTC	VONA REPORT				Estimated Heigh of Eruption Cloud (m) Padang Weather Radar			
			Ash-Cloud Movement	Estimated Ash-Cloud Top (m)	Seismogram		E-W	NW-SE	N-S	NE-SW
					Max. Applitude	Max. Duration				
22-Dec-2023	07.40	00.40					3270	3270	3270	3270
	12.19	05.20 (05.19)	Ash-Cloud not observed	Ash-Cloud not observed	Eruption and emission are continuing		4930	5700	6670	6630
	14.30	07.30					3270	3230	2500	1510
	16.10	09.10					4430	3330	4570	3300
	16.30	09.30					3230	3230	3270	3270
	19.10	12.10					-	3300	3270	3270

The analysis of Padang weather-radar data for the Mount Marapi eruption on 22 December 2023 yielded strong results, where the observations detected six volcanic-ash emission events with varying heights that are not observed by visual observation VONA. The results were summarized in Table 2. This indicates that Mount Marapi experiences volcanic-ash emissions continuously over time with different emission levels and volumes of eruption material at each activity.

5. Discussions

The results of radar data analysis on the eruption of Mount Marapi in Figure 4 could answer that the closure of Minangkabau International Airport was due to the volcanic ash emission activity that occurred continuously even in a short period. This research demonstrated that weather radar could detect volcanic-eruption activity in greater detail than visual observations that could not provide precise information on the height of volcanic ash emissions. Weather radar observations were able to detect eruptive activity and volcanic ash emissions, although no eruption clouds were produced during the eruption as reported in the VONA report. A key limitation of visual observation was that the eruption produced only volcanic-ash emissions, with no formation of eruption clouds. The size of volcanic ash material with intensity <15 dBz in the form of Fine Ash (FA) as in the research of (Marzano et al., 2013) in Table 1 was impossible to observe visually without technological assistance. This results in low accuracy in determining the height of volcanic-ash emissions in the VONA report.

Compared to previous studies, the process of retrieving information and conclusions related to eruption height information and eruption particle upright cross-section in this study was significantly faster because it used standard products with parameter modifications, without requiring data conversion or reconstruction. This rapid process could improve the speed and accuracy of providing information on volcanic ash detection and distribution forecasts to airport authorities and stakeholders.

Another interesting point from the analysis of Padang weather radar data observations in the case of Mount Marapi eruptions was that the difference in the volume of volcanic ash emissions detected in each eruption activity can indicate the volume of volcanic ash material released into the atmosphere. The accumulated volume of volcanic ash material from the six eruptions observed by weather radar was distributed primarily toward the south–southwest towards Minangkabau International Airport. This caused the airport authority to take action to divert several flights and temporarily close airport operations.

From the discussion, weather radar technology showed good capability and performance in observing eruption activity and measuring the height of volcanic ash emission even though no eruption clouds formed, suggesting that this technology could serve as a primary tool for observing volcanic-eruption activity. Then, to optimize weather radar observations during volcanic eruptions and increased activity, especially in generating volcanic ash height information, it is necessary to modify the observation parameters such as sampling range, antenna speed, PRF (Pulse Repetition Frequency), and noise filtering that adjust to the distance of the radar to the volcano. This modification will improve the accuracy of weather radar observations in detecting volcanic activity and observing the height of volcanic ash that occurs both when eruption clouds form or do not form.

6. Conclusions

The results of this research analysis showed that weather radar technology could fill the gap in technological capability for observing volcanic activity by providing more detailed information about the estimated distribution and height of volcanic ash. The results can be used to add information to the VONA report to improve flight safety. Weather radar observations have the opportunity to serve as the basis for decision-making by airport authorities to issue volcanic ash early warnings that impact the safety of flight operations and local governments regarding general public safety. Therefore, in future research, it is necessary to conduct research on volcanic eruption events with a wider variety of eruptions and emissions to build awareness and understanding of the ability of weather radar in observing volcanic eruption activity.

However, to improve the accuracy and effectiveness of observations, it is necessary to modify the weather radar observation mode when there is volcanic eruption activity in the radar observation area, such as Volume Coverage Pattern (VCP) 31 which is commonly used in clear air mode. This mode has better detection sensitivity in clear air conditions with a scanning interval time of every 5 minutes.

7. Abbreviations

Abbreviation	Full Term
ANT3D	Analytical Tools for Three-dimensional Weather Radar Data
BB	blocks and bombs
BMKG	Badan Meteorologi Klimatologi Geofisika
CA	coarse ash
CDM	Collaborative Decision Making
CMAX	Column Maximum
FA	fine ash
ICAO	International Civil Aviation Organization
I-WISH	Integrated Web Based Aeronautical Information System Handling
LL	large lapilli
MCA	the mass-continuity approach
MER	mass eruption rate
MSL	Mean Sea Level
NOTAM	Notice to Airmen
PRF	Pulse Repetition Frequency
PVMBG	Pusat Vulkanologi & Mitigasi Bencana Geologi
SFA	surface-flux approach
SL	small lapilli
TPA	top-plume approach
UTC	Coordinated Universal Time
VAAC	Volcanic Ash Advisory Center
VARR	volcanic ash radar retrieval
VCP	Volume Coverage Pattern
VCUT	Vertical Cut
VONA	Volcano Observatory Notice for Aviation
WIB	Waktu Indonesia Barat

8. CRediT Statement

Hesti Heningtiyas: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing original draft, Visualization.
Asep Adang Supriyadi: Validation, review & editing, supervision, funding acquisition.
Syachrul Arief: Validation, review & editing, supervision.

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