

Statistical Analysis of Volcanic Ash Measured by X-band Polarimetric Radar

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(Dated: 18 July 2014)

1. Introduction

While it is recognized that weather radar can detect volcanic ash, the methods of the physical approaches (e.g., Marzano et al., 2006; Marzano et al., 2012) and engineering approaches (Maki et al., 2012) to quantitative ash estimation (QAE) that have been proposed have not been fully validated because frequency of volcanic eruptions is limited. Sakurajima volcano in Kagoshima, Kyusyu provides us with useful data to establish a QAE algorithm. According to the Japan Meteorological Agency (JMA) report, the total numbers of explosive eruptions per year from 2009 to 2013 were 755, 1026, 1355, 1107, and 1097, respectively. In Kagoshima City, there has been an increase in ash accumulation corresponding to volcanic activity, with a total ash amount of 3,500 gm⁻² recorded in 2011 at the Kagoshima local meteorological observatory.

There have been several reports of ‘conventional’ radar succeeding in detecting volcanic eruptions and in estimating ash amount distributions. Additionally, ‘polarimetric’ radar may have the potential to deduce the microphysical properties of volcanic ash particles such as ash particle size distribution, particle shape and postural. By analogy with past studies of hydrometeor classification in radar meteorology, polarimetric radar parameters may be used to discriminate ash particles from hydrometeors, which is a difficult task for non-polarimetric radar.

Since 2011, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has operated X-band operational polarimetric radar at a location 10.7km from the Showa crater. The present study examines the potential use of operational polarimetric weather radar in the detection of volcanic eruptions, and for quantitative ash fall estimations (QAE).

2. Data

2.2.1 Radar data

The radars used in the present study are MLIT X-band operational polarimetric radar (TRM), C-band polarimetric radar, and JMA C-band terminal Doppler radar (KGS, TNG). Figure 1 shows the locations of the radars and their observation areas. Table 1 also shows the main specification of the radars and their time and space resolution. To develop quantitative ashfall estimations, a total of 31 eruptions in 2013 were selected, under the condition that the maximum ash height of each eruption was higher than 3000m above the crater. This condition is thought to be necessary because of the scanning strategy of the X-band polarimetric radar, where its sensitivity is not enough to disperse the ash distributions of small eruptions.

Among three operational C-band radars are also available for ash measurements, the most utilized radar may be a C-band terminal Doppler radar (KGS) that is located about 24.5 km from the Showa crater. Its maximum observed height and radar beam width above the crater are 13300 and 300 m., respectively. The Kuminiyama C-band polarimetric radar (KNM), located about 45.5 km from the crater, is operated with two PPI scans at elevation

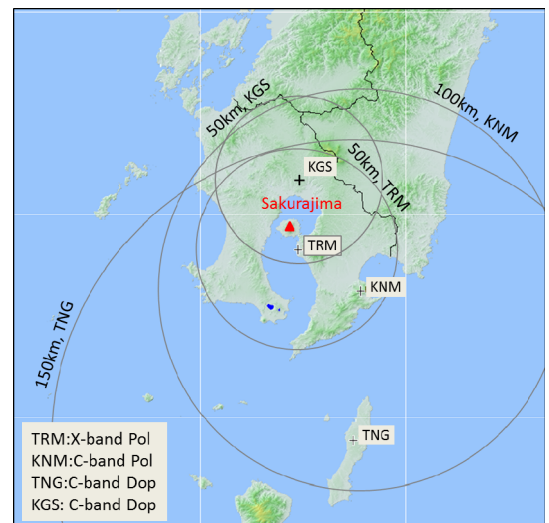


Fig.1 Locations and observation areas of operational radars.

angles of 0.4° and 0.8° . Although the radar has polarimetric function, the maximum beam observable height is 700 m above the crater and the beam width is about 1100 m which are not enough spatial resolution for ash measurements. The JMA C-band Doppler radar (TNG) is located about 109 km from the crater. This radar is located far from the crater so that high resolution measurements are not effected; the radar's minimum height and beam width above the crater are 2700m and 1900 m, respectively.

Table 1 List of operational radars.

| Radar (Name) | Location Latitude / Longitude | Antenna Size, Gain Speed, Beam Width | Transmitter Frequency, Peak Power PRF, Pulse Length | Receiver Smin |
|-------------------------|---------------------------------|---|---|---------------|
| TRM (Tarumizu) | N 31°29'19.7" E 130°41'40.8" | 2.2m ϕ , 44.7dB(H),45.1dB(V) 3.5/4.0rpm, 1.0° | 9770MHz, 200W, 1500/200pps, 1.0/32 μ s | -109 dBm |
| KNM (Kunimiyama) | N31°18'27.0" E130°00'56.0" | 4m ϕ , 45.2dB 1rpm, 1.0° | 5260MHz, 250kW, 280pps, 2.5 μ s | -109 dBm |
| TNG (Tanegashima) | N 30°38'21.8" E 130°58'42.7" | 4m ϕ , 44.4dB(H) 4rpm, 1.0° | 5350MHz, 250kW, 940/752pps*, 1.1 μ s*, | -108 dBm |
| KGS (Kagoshima airport) | N31°47'41.2" E130°43'10.6" | 7m ϕ , 48.9dB(H) 2 or 4 rpm, 0.6° | 5370MHz, 200kW, 1200/960pps, 1.0 μ s | -110 dBm |

2.2.2 Ground truth data

The locations of ground truth data measurements are shown in Fig. 3. MLIT set up 20 manual ash collectors and 18 automatic ash collectors on Sakurajima. In addition to the ash collectors, a 2DVD was set up in Kagoshima in 2012 to measure ash particle size distribution. Measurements with a parsivel were done in 2014. The quality checks of obtained data are ongoing for scattering simulations. In addition to these fixed point measurements, mobile measurements with an automatic electric balance and manual ash sampling with paper cups were employed in 2014. The ground truth measurements were not allowed within the off-limits area, which is designated as a 2km radius out from the crater.

3. Preliminary Results

3.1 Accumulated radar reflectivity

The accumulated radar reflectivity of X-band polarimetric radar was calculated for each eruption. The radar detected echoes associated with eruptions. Figure 2 shows the result for an eruption that occurred on 18 August, 2013. The ash flew over the Kagoshima downtown area, which is located about 11 km west of the crater.

3.2 Quantitative ash estimation based on X-band polarimetric radar

Two types of QAE will be proposed: an engineering approach and a physical approach. The former uses radar data and surface data to find the relationship between the two parameters. An example of this type of approach is the Z-R relationship in the fields of radar meteorology and radar hydrology. The latter method uses a scattering simulation,

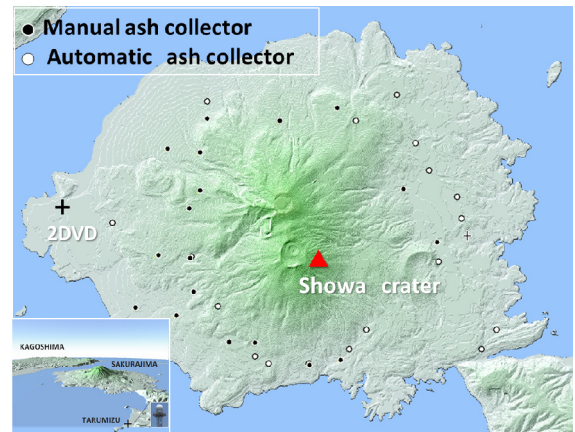


Fig.2 Locations of MLIT operational ash collectors.

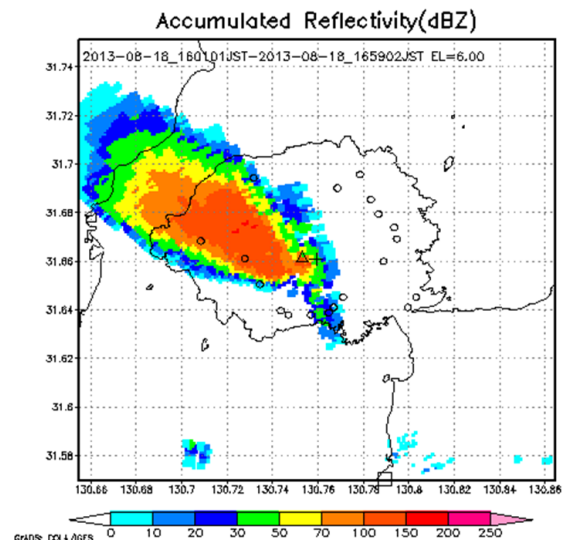


Fig.3 Distribution of accumulated reflectivity (16:00-16:59JST, 18 August 2013).

based on the physical ash particle properties, to obtain the relationship between the ash amount and the polarimetric parameters.

Figure 4 shows a scatter plot of accumulated reflectivity (S_Z) and surface face ash amount (S_A). Data from a total of 6 eruptions are used for the analysis. The obtained relationship between S_A and S_Z is $S_A = 1.32 + 0.118 \times S_Z$, where S_Z (dBZ) and S_A (dBg⁻¹m⁻²). The relationship is close to that of the eruption of Sin-Moedake, 26-27 February, 2011.

3.3 Experiments on fundamental ash properties

Quantitative ash fall estimation based on the physical approach requires basic ash particle information such as size distribution, shape, and terminal fall speed. We conducted experiments to obtain the basic properties of volcanic ash particles which are necessary for quantitative ash estimation by weather radar. The ash particle samples used in the experiments, listed in Table 1, were collected at several points on Sakurajima Island. Samples Arimura 1 and Arimura 2, collected at points 2.1km and 3km from the crater respectively, were divided into 7 groups based on their size. Samples MLIT 1 and MLIT 2 were collected by automatic ash collectors set up by MLIT at 18 points on Sakurajima. The experiments were carried out in the NIED rainfall simulator where ash particles can be dropped from a height of 17m, which height is necessary for the ash particles to attain terminal velocity. A 2DVD, a parsivel, and an electric balance were set up on the ground to measure the falling velocity, particle size distribution, shape, and the canting angle of the falling ash particles (the later items can only be measured by 2DVD).

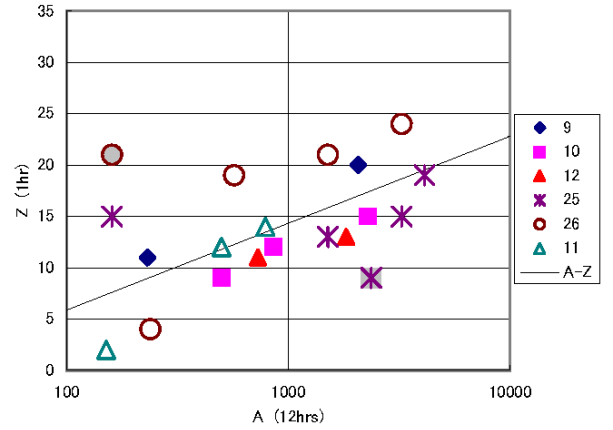


Fig.4 Relationship between accumulated reflectivity and surface ash amount.

Table 1 List of volcanic ash particle samples collected on Sakurajima, Japan

| Sample Name | Description | Location of sampling point |
|-------------|---|--|
| Arimura 1 | 7 size classes (from 3ϕ to -3ϕ)* | 2.1km from the crater, collected in March 2014 |
| Arimura 2 | 7 size classes (from 3ϕ to -3ϕ) | 3 km from the crater, collected in Jun 2014 |
| MLIT 1 | Operational ash measurements | 18 points, collected on 28 Feb., 2014 |
| MLIT 2 | Operational ash measurements | 18 points, collected on 31 Mar., 2014 |
| MLIT 3 | Operational ash measurements | 18 points, collected on 30 Apr., 2014 |

* ϕ is the scale of particle size defined by $\phi = -\log_2 D$ where D (mm) the diameter.

3.4 Statistical properties of polarimetric radar variables of ash fall

The quantitative ash estimation (QAE) based on physical approach requires statistical characteristics on polarimetric radar variables in addition to the fundamental physical properties on ash particle mentioned in the previous section. From the preliminary analysis, differential reflectivity Z_{DR} over a volcano crater fluctuates in space and time during eruption period, while showing significant spatiotemporal patterning in the downwind regions; time change of intensities Z_H and Z_{DR} shows opposite tendency (Fig. 5). This observation result suggests the presence of an ash particle aggregation and sorting mechanism. On the other hand, the specific differential phase shift K_{DP} is not useful for QAE.

The radar cannot detect weak ash echoes due to the minimum detectable reflectivity (MDR), which depends on the range from the radar and the receiver noise level of the radar system. According to statistical analysis of Z_H , MDR of TRM radar is about 5 dBZ over the crater under the non-precipitation condition.

The correlation coefficient ρ_{hv} is one of important parameters for discrimination between precipitation and ash particle. Statistical analysis of polarimetric radar variables are now investigating for

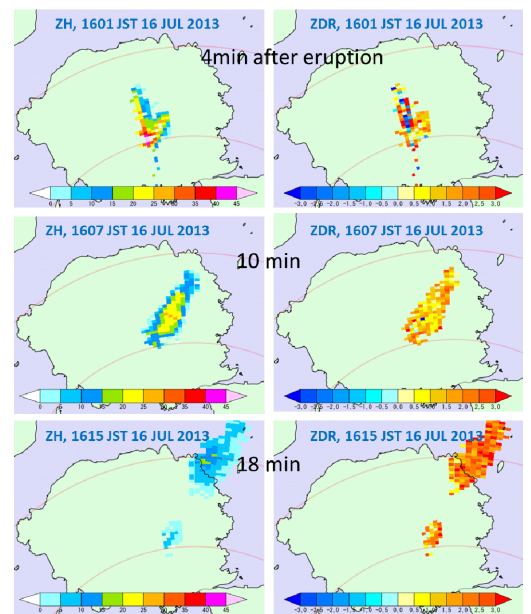


Fig.5 Time change of Z_H and Z_{DR} of the eruption at 16:31JST, 18 August, 2013.

establishing particle classification algorithm. We have also corrected several radar data of volcanic eruptions during rain which is useful to validate the developed ash discrimination algorithm.

4. Summary

The present study focuses on the utilization of operational weather radar for quantitative ash estimation (QAE) and quantitative ash forecasting (QAF). The radar data analyzed in the present study are from eruptions of the Sakurajima volcano in Kagoshima Prefecture, Japan. Based on data from 31 explosive eruptions of the Sakurajima volcano in 2013, we reach the following conclusions:

- 1) Operational polarimetric weather radar has the potential ability to quantitatively estimate the amount of volcanic ash expelled during volcanic eruptions.
- 2) The Z-A relationship is derived using ground measurements of the ash amounts.
- 3) The differential reflectivity over a volcano crater fluctuates in space and time, while showing significant spatiotemporal patterning in the downwind regions, which suggests the presence of an ash particle aggregation and sorting mechanism.

Acknowledgments

The authors thank the Osumi Office of Rivers and National Highways, the Kyusyu Regional Development Bureau, and the Ministry of Land, Infrastructure, Transport and Tourism for the provision of X-band polarimetric radar data and ground surface data.

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