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Can we use weather radar to retrieve volcanic ash eruption clouds? A model and experimental analysis

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1 Introduction

Real-time areal mapping of a volcanic eruption, in terms of its intensity and dynamics, is usually not possible by conventional visual inspection, especially during poor visibility expected in those circumstances (Barberi et al., 1990). In order to monitor ash cloud patterns, aircraft observations have a limited value, due to their non-systematic nature and inherent hazards for flights within an ash cloud (Rose and Schneider, 1996). In this respect satellite measurements can offer the advantage of a global coverage with a known temporal repeatability. Satellite visible-infrared radiometric observations from geostationary satellites (e.g., Meteosat sensor) are usually exploited for long-range trajectory tracking and for measuring low level eruptions. Their imagery is available every 15-30 minutes and suffers from a relatively poor spatial resolution (i.e., order of some kilometers). Moreover, the field-of-view of geostationary radiometric measurements may be blocked by water and ice clouds at higher levels and their overall utility is reduced at night.

It should be noted that many volcanic cloud encounters have happened only minutes to a few hours after eruptive events so that timely information on the eruption's onset and its intensity is vital. Among the remote sensors, ground-based microwave weather radars may represent an important tool to detect and, to a certain extent, mitigate the hazard from the ash clouds (Harris and Rose, 1983). The possibility of monitoring 24 hours a day, in all weather conditions, at a fairly high spatial resolution (less than few hundreds of meters) and every few minutes after the eruption is the major advantage of using ground-based microwave radar systems. Ground-based weather radar systems can also provide data for determining the ash volume, total mass and height of eruption clouds (Marzano et al., 2005). The latter information is especially valuable because a series of column height measurements allows the mass and dynamics of an eruption to be directly monitored. Moreover, the altitude of the cloud top above the vent represents an essential datum both to aviation safety and early warning and to ash cloud trajectory models able to forecast the position of volcanic clouds after an eruption based on winds aloft (Lacasse et al., 2004).

In spite of this potential and the fact that weather radar use dates back to early eighties, there are still open issues about microwave weather radar capabilities to quantitatively retrieve volcanic ash cloud parameters. Single-polarization Doppler radars can measure horizontally-polarized power echo and Doppler frequency shift from which ash content and radial velocity can be revealed. Several unknowns condition the accuracy of radar products, most of them related to the micro-physical variability of ash clouds such as their particle size distribution, shape and dielectric composition. Even though this variability cannot be fully resolved by using the available observables of Doppler microwave radars, the accuracy of radar remote sensing of volcanic eruptions can be quantitatively assessed by estimating the uncertainty of micro-physical and scattering models of ash clouds.

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In this work, the potential of using ground-based weather radar systems for volcanic ash cloud detection and quantitative retrieval is evaluated from a modeling point of view. In order to do this, microwave radar sensitivity to ash clouds is examined and using available data at C band during the eruption of Mt. St. Helens volcano.

2 Radar observations of volcanic ash clouds

Materials of all types and sizes, erupting from a crater or volcanic vent as a result of an intensive magma and rock fragmentation, are usually referred to as tephra. Among tephra, volcanic ash is made by small particles (<2 mm in average diameter) of pulverized rock blown from an explosion vent. Ash clouds are transported and their particles are sorted by prevailing winds and eventually fall through the air (ashfall) resulting in a deposit that is well sorted and layered (Wohletz et al., 1989).

Volcanic ash is formed by volcanoes through several different processes that transform large batches of magma and country rock into smaller pieces. Two general mechanisms can be identified: i) magmatic fragmentation in which the evolution and expansion of magmatic gases contribute to volcanic ash production; ash particles are usually marked by the presence of vescicles and production of pumice; ii) hydrovolcanic (also called phreato-magmatic) fragmentation in which physical contact and mixing of magma with external water result in ash particle formation; the propagation of stress waves through the magma and instabilities at the interfaces between magma and water can contribute to ash production.

Ash cloud particles consist mainly of angular shattered rock fragments and have a quite irregular and complex shape. They can be categorized as vescicular, non-vescicular and miscellaneous. The diameters of particles in fall deposits typically range from a few microns or less to several centimeters or more. Both the concentration and diameter of particles in the volcanic clouds decrease with distance from the vent be-cause larger particles tend to fall out quickly. Generally, finer particles (<10 µm in average diameter) can stay sus-pended for days to months and can be transported to great distances from the volcanic source. Analogously, coarse ash (<64 µm in average diameter) may have a relatively long atmospheric residence time (more than several hours), whereas lapilli (>1 mm in average diameter) tend to fall out within an hour. Bombs or blocks (>64 mm) across ejected by the explosion typically fall within a few kilometers of the eruption site very rapidly (within few minutes).

It is worth mentioning that, with respect to rainfall, ashfall has some important differences: i) ashfall amounts and size distributions are preserved for very long periods (till millions of years) after deposition, except for aggregation of fine ash; ii) the ash PSD is mainly established by explosive fragmentation rather than by reversible processes such as condensation, evaporation, coalescence and breakup. In contrast with rain clouds, since ash clouds can be a major hazard to air flights, in situ sampling of ash clouds by aircraft is not possible except during very light ashfall. The use of the radar to observe ash eruptions is quite limited, indeed, and most radar observations of volcanic eruptions are occasionally carried out by meteorological radars of national weather services.

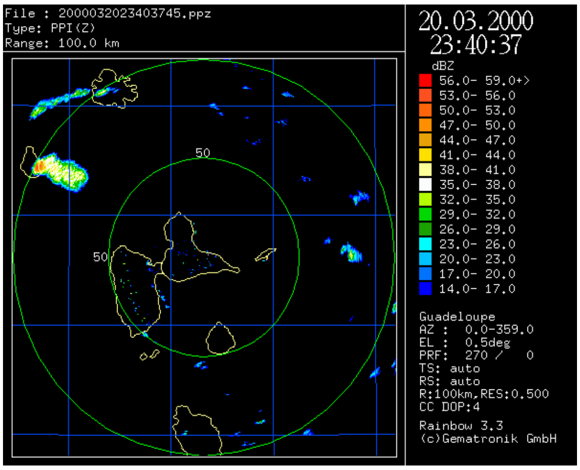

Fig. 1. Plan Position Indicator (PPI) of horizontally-polarized radar reflectivity factor (dBZ), measured by S-band weather radar of Guadeloupe during Soufriere Hill volcano eruption on March 20, 2000 at 23:40 UTC (courtesy of Meteo France, Gaudeloupe).

Some recent episodes of volcanic ash radar detection are qualitatively analyzed in Figs. 1 and 2. Fig. 1 shows the eruption of Soufriere Hills volcano, occurred on 20 March 2000 and monitored by S-band radar located at Guadaloupe Island. Note that horizontally-polarized reflectivity data, as usual, are calibrated with the dielectric factor of water (i.e., equal to 0.93). Due to the distance between radar and volcano (about 100 km) it is a remarkable example of capability of S-band weather to detect ash cloud with reflectivity values up to 55 dBZ near the volcano vent mainly due to coarse ash and lapilli ejection.

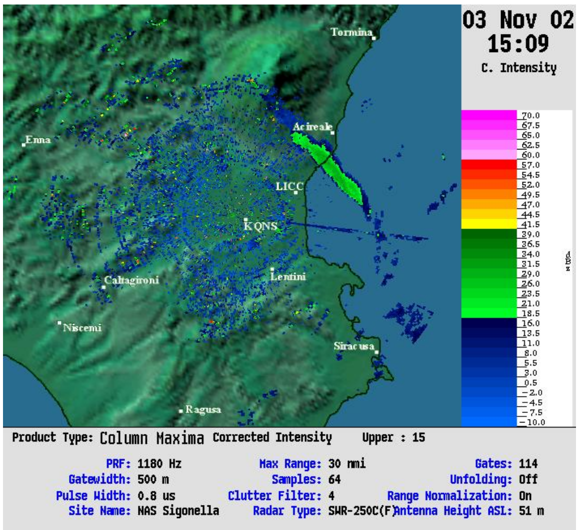

Fig. 2. Plan Position Indicator (PPI) of horizontally-polarized radar reflectivity factor (dBZ, named also corrected intensity), measured by C-band weather radar of Sigonella (Sicily, Italy) during Mt. Etna volcano eruption on Nov. 03, 2002 at 15:09 UTC (courtesy of NATO Sigonella base, Italy).

Another example is the radar observation of the Mt. Etna eruption that began on Oct. 27, 2002. This eruption resulted in the total destruction of the tourist complex and ski-ing area and a portion of a pine forest. Eruptive activity on the North-Eastern flank produced the main lava flows and ended on Nov. 5, while less lava but a large volume of pyroclastics was produced on the Southern flank with an activity that continued till Nov. 16, 2002. Heavy ash falls mostly affect the Catania area, repeatedly forcing the closure of Catania airport. Eruptive seismicity and ground deformation caused damage on the northeastern and eastern flanks. As shown in Fig. 2, C-band radar images were taken from US Navy station of Sigonella (Sicily, Italy), about 40 km far from the vent. In this case, due to widespread meteorological clouds over Sicily, the Meteosat geostationary satellite couldn't map the ash eruption, while the C-band radar clearly detected the ash cloud dispersion. In this snapshot ob-served reflectivity values were not higher than 30 dBZ due to the fact the ash cloud was already relatively far (about 10 km) from the volcano vent and mainly constituted by fine and coarse ash.

3 Radar scattering model of volcanic ash

Ash particle occurrence per unit volume and unit size can be described by the particle size distribution. A general scaled form has been assumed in this work to describe ash particle size distribution (PSD) [$mm^{-1}\cdot m^{-3}$], formally expressed by (Marzano et al., 2005):

$$N_a(D) = N_n \left(\frac{D}{D_n}\right)^{\mu} e^{-\Lambda_n \left(\frac{D}{D_n}\right)^{\nu}} \qquad (1)$$

where D [mm] is the particle diameter, D_n [mm] the number-weighted mean diameter and, in a logarithmic plane, N_n [$mm^{-1}m^{-3}$] the intercept, Λ_n the slope, μ the shape factor and ν the slope factor. The PSD normalization is such that N_n and Λ_n are related to mean diameter D_n and ash concentration C_a. The form of (1) is quite general and its derivation is detailed in previous works. It is demonstrated that (1) may represent both the scaled Weibulll PSD (SW-PSD) with $\nu=\mu+1=3\gamma+3$ and the scaled Gamma PSD (SG-PSD) with ν=1. In particular, the scaled Weibull PSD is shown to be derivable from the Segmentation-Fragmentation Theory (SFT) where particle transport and growth are taken into account in a physical manner (Wohletz et al., 1989). The maximum-likelihood best-fitting of (1) with respect to available PSD ash measurements has shown that the most probable value of μ is about 1 and 0.5 for a scaled-Gamma and scaled-Weibull PSD, respectively .

From the knowledge of ash PSD, shape and composition, some meaningful parameters can be introduced by indicating with m_n the order-n moment of a given PSD. If ρ_a [$g\cdot cm^{-3}$] is the ash density and $m_a=\rho_a(\pi/6)D^3$ the mass of sphere-equivalent ash particles, then the *mass concentration* C_a [$g\cdot m^{-3}$] can be expressed by:

$$C_a \equiv 10^{-3}\int_{D_1}^{D_2} m_a(D) N_a(D) dD = \frac{10^{-3}\pi}{6}\rho_a m_3 \qquad (2)$$

where D_1 and D_2 are the minimum and maximum diameter [mm] and m_3 is the third-moment of PSD, whereas the *number-weighted mean diameter* D_n [mm] is defined by:

$$D_n = \frac{\int_{D_1}^{D_2} D N_a(D) dD}{\int_{D_1}^{D_1} N_a(D) dD} = \frac{m_1}{m_0} \qquad (3)$$

The factor 10^{-3} in (2) comes from a dimensional analysis of C_a given in [$g\cdot m^{-3}$]. In this work we have considered the scaled-Weibull PSD with μ=3γ+2 as a reference model. If D_1=0 and D_2=∞, the SW-PSD moments of order n are given by:

$$m_n = \frac{\left[\Gamma\left(1+\frac{1}{3(\gamma+1)}\right)\right]^3 \Gamma\left(1+\frac{n}{3(\gamma+1)}\right)}{\frac{\pi}{6}\cdot\Gamma\left(\frac{\gamma+2}{\gamma+1}\right)\cdot\left[\Gamma\left(1+\frac{1}{3(\gamma+1)}\right)\right]^n} \frac{D_n^{\,n-3}}{\rho_a} C_a \qquad (4)$$

where Γ is the complete Gamma function and γ=-0.5 (being μ=0.5 for SW-PSD).

If a Rayleigh scattering regime holds, from (1) the horizontally polarized radar reflectivity factor Z_H [$mm^6\cdot m^{-3}$] is:

$$Z_H = \frac{\lambda^4}{\pi^5 |K_a|^2}\eta_H = \int_{D_1}^{D_2} D^6 N_a(D) dD = m_6 \qquad (7)$$

where η_H is the radar reflectivity, K_a is the complex dielectric factor and λ the radar wavelength. The average value of $|K_a|^2$ is about 0.39 at microwave. The reflectivity factor Z_H is proportional to the sixth power of the particles diameter and, consequently, the larger particles tend to provide a much larger contribution to the reflectivity factor than smaller particles of equal abundance. For brevity, hereinafter the term radar reflectivity will also stand for radar reflectivity factor.

4 Comparison with available radar data

Microwave radar data of volcanic eruptions are not easy to obtain being the latter rare events in some specific geographical areas, not always covered by a scanning weather radar. Some of the best reported events are those of March 19, 1982 and Mount St. Helens eruptions of May 18, 1980 (Harris and Rose, 1983).

The eruption of March 19, 1982 started at 19:28 UTC with a small Plinian column associated to a high amplitude tremor. The major ash eruption was probably produced in a short interval of about 40-50 seconds. The ash cloud was detected and tracked by the National Weather Service C-band radar, located in Portland, Oregon, USA. The maximum height of the ash column was measured at 13.7 km above the sea level around 19:38 UTC. This height decreased with time owing to gravitational settling of ash particles, while the root mean square size of the ash cloud was about 15 km. Radar reflectivity factors, inferred from estimated ash PSD, may have been as high as 24.7 dBZ, but would have decreased within 10-20 minutes to less than 1 dBZ owing to the fallout of particles larger than 1 mm. Between 20:00 and 20:30 UTC measured reflectivity factors were between 0.3 and 8.6 dBZ with an average value of 4.5 dBZ. These Z_H values correspond to an average ash mass concentration of about 0.19 g m^{-3}., as derived from deposited ashfall data.

The case study of the eruption on May 18, 1980 was significantly different from that on March 19, 1982. The duration of the Plinian phase was about 9 hours. The ash volume of May 18 eruption is a factor 10^3 larger than the one of March 19 and was observed not only from Portland radar, but also from 2 other aviation radars at 0.7 GHz in Seattle and Spokane (Washington). Although the eruption was long lasting, the magma eruption rate was strongly varying with time. The 6-hour mean ash concentrations decreased from about 3.7 g m^{-3} at 57 km from the volcano, to lower values at greater distances as the sizes of the largest ash particles decreased due to fallout. Corresponding average reflectivity factors, measured within the same interval of 6-hours, were of the order of 13 dBZ with a variability between 8.4 and 17.6 dBZ due probably to ash clusters within the range of 0.2-0.5 mm. Aggregation of fine ash might have caused an enhancement of observed radar reflectivities.

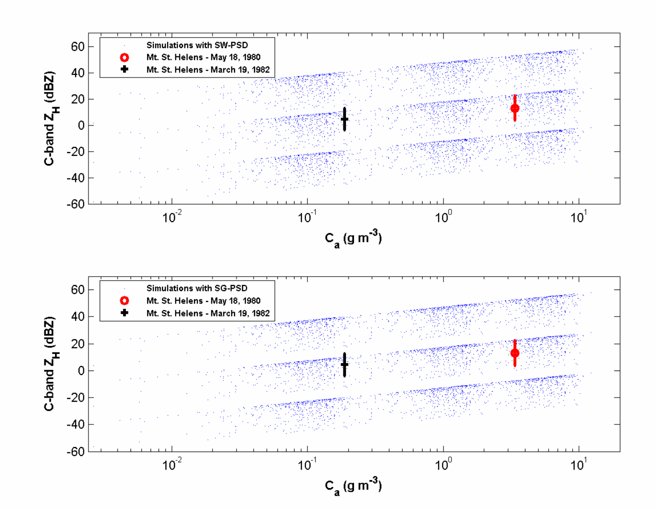

Fig. 3. Scatterplot of simulated C-band reflectivity factor Z_H and ash concentration C_a for the size classes of fine ash, coarse ash and lapilli, defined in Tab. II, using a scaled-Weibull (top panel) with γ =-0.5 and scaled-Gamma with μ=1 (bottom panel) with ρ_a=1 g cm^{-3}. "Plus" and "cross" marks show the measured Z_H and C_a derived from Mount St. Helens eruptions of May 18, 1980 and March 19, 1982, respectively, with an observed variability denoted by the error bars.

Fig. 3 shows the Z_H-C_a relationship in a logarithmic plane utilizing the scaled-Weibull PSD with γ=-0.5 and, for comparison, the scaled-Gamma PSD with μ=1. Simulated results for three size classes (fine ash, coarse ash and lapilli) are plotted. The labeled marks show average measured reflectivity factor Z_{Hm} and C_a estimated for Mount St. Helens eruptions of May 18, 1980 (characterized by mean $\langle Z_{Hm}\rangle$=13.0 dBZ and $\langle C_a\rangle$=3.4 g m^{-3}) and March 19, 1982 (characterized by mean $\langle Z_{Hm}\rangle$=4.5 dBZ and $\langle C_a\rangle$=0.2 g m^{-3}). The bars around $\langle Z_{Hm}\rangle$ indicate the observed variability of reflectivity measurements. It is worth mentioning that all meteorological radar are calibrated with the dielectric factor of water, i.e. $|K_w|^2$=0.93 in $Z_{Hm}=(P_r r^2)/(C|K_w|^2)$ where P_r is the received power, r the range and C the radar instrumental constant. We know that the equivalent reflectivity factor of ash particles is given by $Z_{Ha}=\eta_H(\lambda^4/(|K_a|^2\pi^5))$. This means that we need to rescale our Mie scattering simulations of Z_{Ha} into water-equivalent reflectivity factor Z_{Hw} through $Z_{Hw}=Z_{Ha}-3.77$ (in dBZ) since $|K_a|^2/|K_w|^2$=0.42.

The radar measured data refer to places relatively far from the volcano vent and later in time with respect the eruption paroxysm. The Mount St. Helen measurements seem to be well explained by Z_H-C_a simulations of coarse ash class (with $\langle D_n\rangle$=0.1 mm) both for May 18, 1980 and for March 19, 1982 case study, consistently with ground observations. The ash regimes are, however, quite different being the eruption of 1980 much more intense then that of 1982 with an average concentration of two orders of magnitude larger. The choice of a particular PSD does not substantially affect this interpretation of the measured results, being their differences well within the ash class variability.

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5 Conclusions

This is a preliminary work on volcanic ash radar retrieval and its physical foundations. The aims of the overall work is devoted to the gathering of extensive ash data sets relative to various volcano eruptions in order to better tune the PSD parameters of both scaled Gamma and Weibull models. Indeed, ash deposits are an indirect characterization of ash clouds and in this respect in situ ash measurements should represent the proper validation even though difficult to get. Any ash cloud retrieval algorithm should be then tested against weather radar measurements in a quantitative framework. Recent experimental campaigns and C-band radar measurements in Iceland might represent a unique opportunity in this perspective (Lacasse et al., 2004).

References

Barberi, F., G. Macedonio, M. Pareschi, and R. Santacroce, 1990, Mapping the tephra fallout risk: an example from Vesuvius, Italy, *Nature*, **344**, 142–144.

Harris, D.M. and W.I. Rose, 1983, Estimating particle sizes, concentrations and total mass of ash in volcanic clouds using weather radar, *J. Geophys. Res*, **88**, 10969-10983.

Lacasse, C., S. Karlsdóttir, G. Larsen, H Soosalu, W. I. Rose and G.G.J. Ernst, 2004, Weather radar observations of the Hekla 2000 eruption cloud, Iceland, *Bulletin of Volcanology*, **66**, pp. 457–473.

Marzano F.S., E. Picciotti, G. Ferrauto, Vulpiani, and W.I. Rose, "Volcanic ash remote sensing by ground-based microwave weather radar", Proc. of EGU05 General Assembly, Wien (A), 25-29 April 2005.

Rose, W. I. and D. J. Schneider, 1996, Satellite images offer aircraft protection from volcanic ash clouds", *EOS*, v77, 529-532.

Wohletz K.H., M.F. Sheridan and W.K. Brown, 1989, Particle size distributions and the sequential fragmentation/Transport-Theory applied to volcanic ash, *Geophys. Res. Lett.*, **16**, 15703-15721.