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Ballistics and ash plumes discriminated by Doppler radar

Sébastien Valade[1,2,3] and Franck Donnadieu[1,2,3]

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[1] Small scale eruptive ash plumes at Arenal volcano (Costa Rica) were recorded using a ground-based Doppler radar (VOLDORAD). The time-velocity distribution of the mass load (i.e., Doppler radargrams) exhibits two contrasted dynamics recorded simultaneously, evidenced by distinctive velocities, life spans, and transit speeds through the radar beam. Synthetic Doppler radargrams computed with a simple ballistic model indicate that the short-lived signal is consistent with the instantaneous projection of ballistics blocks accompanying the ash plume emission. The mass of centimeter- to decimeter-sized ballistics is confidently estimated at 0.5–7 tons, whereas the ash plume mass is loosely constrained at 5.8×10^2 tons, assuming a particle diameter of 2 mm close to the vent. These quantitative estimates of the mass proportion either falling on the slopes of the volcano or ejected into the atmosphere could help in the modeling and monitoring of tephra dispersal. **Citation:** Valade, S., and F. Donnadieu (2011), Ballistics and ash plumes discriminated by Doppler radar, *Geophys. Res. Lett.*, *38*, L22301, doi:10.1029/2011GL049415.

1. Introduction

[2] Small-scale volcanic eruptions commonly expel a wide range of pyroclast sizes, ranging from coarse blocks with ballistic trajectories, to fine ash driven away within ash plumes. As both the plume and the ballistics are emitted simultaneously, it is often difficult to discriminate and to collect quantitative data on both phenomena. Thermal [*Patrick et al.*, 2007; *Marchetti et al.*, 2009] and ultraviolet imagery [*Yamamoto et al.*, 2008] have provided powerful insights into the dynamics of mild strombolian and vulcanian eruptions, shedding light onto the plume rise dynamics and the relative ash/ballistics distribution of the ejecta. In this paper, we describe similar small-scale transient eruptions at Arenal (Costa Rica), monitored with a ground-based Doppler radar (VOLDORAD) [*Dubosclard et al.*, 2004; *Donnadieu et al.*, 2005]. The radar provides quantitative information on exit velocities and mass loading of the ejecta. We show that the time-velocity distribution of the mass load (i.e., Doppler radargram) reveals two distinct dynamics, which discriminates the ballistics and the ash plume transiting through the radar beam. We compute synthetic Doppler radargrams by numerical modeling of the ballistics, and constrain the dynamics and mass loadings of both the ballistics and the ash plume. Such characterization of the near-vent eruptive dynamics has strong potential applications, as the degree of fragmentation and the mass proportion injected into the atmosphere are of interest for hazard mitigation issues.

2. Radar Data Acquisition

[3] VOLDORAD is a ground-based, pulsed Doppler radar, specifically designed for active remote sensing of volcanic jets and plumes [*Dubosclard et al.*, 2004]. The radar was set 2.4 km West of Arenal's active crater C, at an altitude of 685 m. The 27° antenna elevation enabled the beam to skim the summit crater (Figure 1). The spatial resolution is defined by the beam aperture (9°) and the radial depth (120 m) of the successive volumes (range gates) sampled in the beam, referenced by their radial distance to the radar (e.g., 2247 to 2727 m). When volcanic ejecta cross the beam, they scatter some energy of the pulsed electromagnetic waves (100 μs^{-1}) back to the radar. Doppler spectra (acquired at 0.14 s^{-1}), express the power backscattered by the ejecta during the pulse duration (0.8 μs) as a function of their radial velocity (Figure 2a). The backscattered power is a complex function of the number and size of the ejecta. The measured radial velocities inferred from the frequency shift between the transmitted and the backscattered signal correspond to the along-beam components of the ejecta velocities. Positive and negative radial velocities are induced by particles having a radial component of motion respectively away from and towards the radar. Consequently, in the range gates up the vent, ascending ballistics generate mainly positive radial velocities, whereas falling blocks tend to produce negative radial velocities. The juxtaposition of Doppler spectra constitute Doppler radargrams (Figure 2b), which reveal the evolution through time (x-axis) of both the velocities (y-axis) and echo power (color scale) of the ejecta in each range gate. All the useful spatio-temporal information characterizing the target (velocimetry, mass loading, shape of spectra, evolution through the gates) is plotted at once and constitute its Doppler signature.

3. Results

[4] Figure 2b shows the Doppler signature of an eruptive event recorded on February 19, 2004 at 20:00:31 UT. The recording shows two distinct features, characterized by contrasted dynamics, i.e., different life spans, radial velocities, and transit speeds through the radar range gates. The first feature is a short-lived (<15 s) impulsive signal, first appearing at 2607 m as a curved streak. It spreads on a large velocity range (both positive and negative velocities), and transits rapidly through the beam (~3–4 s per gate in average). In the gates above the vent and uphill (i.e., 2607 m and 2727 m), it exhibits sharp onsets, with relatively high positive velocities (>+40 m/s) and high backscattered power

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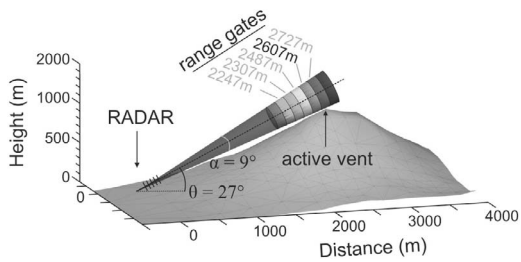

Figure 1. Geometry of the radar sounding at Arenal showing the sampled volumes in the beam. The radar was set up at an altitude of 685 m, 2.4 km West and downwind of the active crater.

(~34 dB in gate 2607 m) reached in <2 s. In both gates, the peak echo power shifts progressively from positive to negative velocities in ~10–13 s (e.g., reaches −30 m/s in gate 2607 m at 20:00:44 UT). In the gates downhill from the vent however (i.e., 2487 m to 2247 m), only negative velocities are recorded: in gate 2487 m for instance, the onset velocity is of −25 m/s, and reaches −48 m/s in ~5 s. Contrastingly, the second feature is a longer-lived signal (≥60 s), whose Doppler signature differs significantly from the short-lived signal: the onsets of both the echo power and the Doppler velocities are progressive, the peak power is 50 times lower (~17 dB), the range of Doppler velocities is similar in all range gates (0 to −15 m/s), the signal lasts 1–2 minutes (e.g., ~84 s in gate 2367 m), and it transits slowly throughout the range gates (~15–20 s per gate in average) with decreasing amplitude. Such Doppler signature is characteristic of an ash plume entrained towards the radar by the wind whose transport speed can be determined in 3-D [*Donnadieu et al.*, 2011].

[5] The occurrence of these two features is observed in several recordings of eruptive events, either simultaneously (e.g., Figure 2), or independently. The differences in the Doppler signature of both point out different dynamics, which suggests that the radar records more than just an ash plume. We hereafter model the short-lived part of the signal to explain its origin.

4. Interpretation and Discussion

[6] Mild explosions typically occur several times a day at Arenal, resulting in small ash-plumes rising to a few hundreds of meters above the vent [*Cole et al.*, 2005]. They are sometime accompanied by blocks impacting the volcano upper slopes, and visible at night as incandescent ballistic projections. We show below with a simple model example that the features of the short-lived signal are consistent with ballistic projections, and we discuss the mass loadings of both the ballistics and the ash plume.

4.1. Modeling Ballistic Projections

[7] We use the 2-D model of *Dubosclard et al.* [2004], to compute the ballistic trajectories of ejecta and the associated synthetic echo power in each range gate. Spherical particles are instantaneously released at selected angles with a velocity depending on the initial gas velocity. Their trajectories are determined by solving the equations of motion

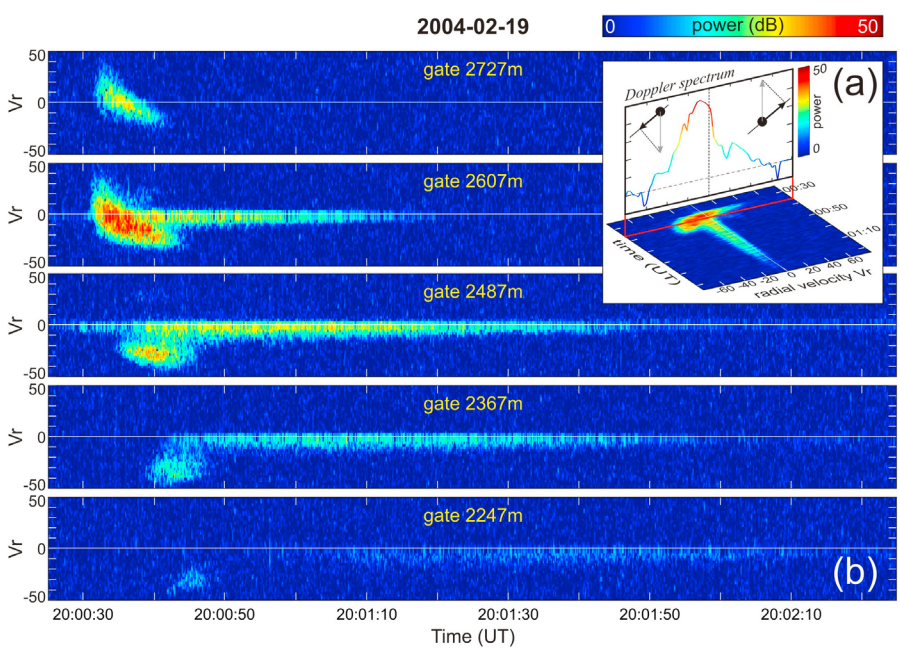

Figure 2. Doppler radargrams recorded during an ash plume emission at Arenal on February 19, 2004 at 20:00:31 UT. (a) The Doppler radargram is built from the succession through time of Doppler spectra. The echo power in the spectrum (dB arbitrary units) is related to the number and size of the particles in the range gate. Positive (right part of the spectrum) and negative (left part) radial velocities correspond to particles with an along-beam velocity component respectively away from the radar antenna and towards it. (b) Doppler radargrams recorded in gates 2247 m to 2727 m, revealing the spatio-temporal evolution of two contrasted event dynamics: the short-lived signal with rapidly changing radial velocities and quickly transiting through the range gates is induced by ballistics, whereas the longer-lived signal with low negative velocities is induced by the wind-drifted ash plume.

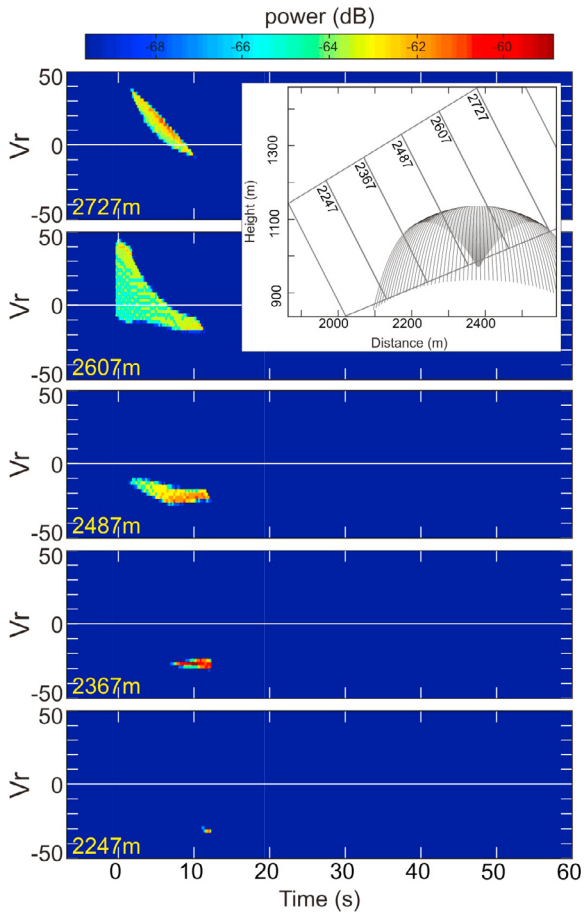

Figure 3. Example of synthetic Doppler radargrams generated with a 2-D ballistic model [*Dubosclard et al.*, 2004; *Gouhier and Donnadieu*, 2010]. 60 spherical particles of diameter 0.1 m were uniformly released in a vertical cone of 60° aperture, with an initial gas velocity of 105 m/s. The source is 20 m below the 2607 m range gate, at x = 2381 m and y = 966 m from the radar. The main features of the short-lived signal observed in Figure 2 are reproduced, indicating its ballistic origin.

under the influence of gas drag and gravity (see *Dubosclard et al.* [2004] for details on the driving equations). The synthetic Doppler spectra are then constructed at each time step by splitting particle radial velocities into classes, and summing the backscattered powers of the particles in each velocity class [*Gouhier and Donnadieu*, 2010]. To reconstruct the evolution of the Doppler signature in the different range gates, Doppler spectra are juxtaposed in time, and a color scale is used for the echo amplitude. Note that this admittedly simple ballistic model was not intended to recover the true eruptive parameters by matching the exact time-velocity distribution of the echo power (which would require inversion procedures, subject of ongoing work), but only to reproduce the main characteristics of the Doppler signature of the short-lived signal using realistic block size and gas velocities.

[8] Figure 3 shows an example of synthetic Doppler signature produced by spheres of 0.1 m in diameter, launched within a vertical cone 60° wide, with an initial gas velocity of 105 m/s. The Doppler radargrams successfully reproduce the main characteristics of the short-lived signal observed in Figure 2b, in particular the transit times, the shape and the number of range gates crossed. The sharp onset in positive velocities at gates 2607 m and 2727 m (+44 and +37 m/s respectively) is successfully reproduced, as well as the decay towards negative velocities during about 10 s. The obtained characteristic curved shape can henceforth be interpreted as mostly resulting from the progressive bending of the ballistic trajectories through the radar beam. As for the gates closer to the radar, the simulation reproduces the onset at moderate and increasing negative radial velocities (−14 m/s in gate 2487 m), the signal onset in the next gate again at higher radial velocities (−27.5 m/s in gate 2367 m), and the progressive diminution of signal duration at increasing distances from the vent (~10.5 s in gate 2487 m against ~1 s in gate 2247 m). Because of the voluntarily simple model, several features of lower importance are not reproduced well: (i) the synthetic power is not as high as the recorded power because of the small number of particles launched in the model; (ii) the spectral width is too narrow, probably because only one particle size and 2-D trajectories are considered. Nevertheless, the reasonable match of the synthetic and observed Doppler signatures strengthens the origin of the short-lived signal as being the instantaneous projection of ballistic blocks crossing the successive range gates.

4.2. Constraints on Mass Loadings

[9] Radar recordings (Figure 2b) have shown that ballistics emitted simultaneously with an ash plume could be discriminated by their distinctive Doppler signature. Using the Mie scattering theory [*Gouhier and Donnadieu*, 2008], the peak echo power of both signals can then be used to constrain the respective masses and volumes of tephra comprising the ballistics and the plume.

[10] Figure 4 shows the solutions for the reflectivity factors close to those measured during the emissions of the ballistics and the ash plume (74.5 and 57.5 dBZ respectively) for

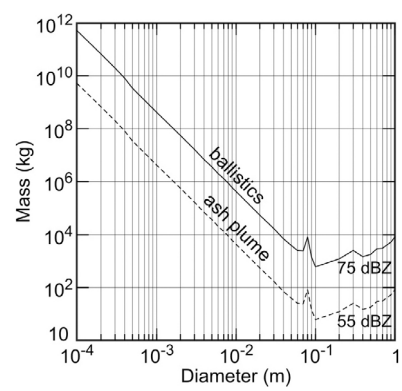

Figure 4. Tephra mass inferred from the Mie scattering theory for various average particle diameters. The two curves indicate the solutions for reflectivity factors close to those measured during the emissions of the ballistics and the ash plume. The mass (assumed density: 1700 kg/m^3) can be well constrained in the case of centimeter- to decimeter-sized ballistics, whereas in the case of the ash plume, it critically depends on the assumed diameter because of the finer grain size distribution.

various particle diameters assumed. The strong power values observed in the short-lived signal (Figure 2b) suggest that they were produced by coarse ballistic particles (blocks), because large particles backscatter much more energy than fine ones. If we consider block sizes ranging between 0.04–1 m and 1700 kg/m^3 in density, the mass of ballistics would fall in the range 0.5–7 tons, i.e., a DRE volume of ballistics of 0.2–2.8 m^3 (density of 2500 kg/m^3). Comparatively, *Cole et al.* [2005] give crude estimates of the total tephra volume of individual explosions at Arenal in the region 10–50 m^3.

[11] For finer grain size distributions, the inferred mass becomes critically dependent on the assumed diameter (Figure 4). Accessing the particle size distribution within the ash plume near the vent is particularly challenging, so we used the coarsest diameter (2 mm) of particles collected by *Cole et al.* [2005] between 2 and 3 km downwind of the vent. Assuming a density of 1000 kg/m^3 (2 mm andesitic ash [*Bonadonna and Phillips*, 2003]), the estimated mass is in the order of 5.8×10^2 tons. Our value likely represents an upper limit for the mass of ash in the plume because (i) the particle size distribution above the vent is highly polydisperse with a diameter mode certainly coarser than the assumed 2 mm diameter, (ii) the particle shapes are likely to deviate from the spherical assumption of the Mie theory, which increases the energy backscattered to the radar [e.g., *Sauvageot*, 1992], and (iii) the ash plume might not completely fill the range gates probed by the radar. To a lesser extent, the ash mass estimate is slightly underestimated because the duration of the ash emission exceeds the plume transit time through the range gates, unlike the ejection of ballistics. More precise estimation of the mass loading of ash plumes would require more stringent constraints on the grain size distribution close to the vent.

5. Conclusions

[12] Ground-based Doppler radars allow the discrimination of ballistics and ash plumes expelled simultaneously. The Doppler radar signatures show two distinct dynamics characterized by different evolutions of the velocity range with time, distinct durations and transit speeds through the radar range gates. In the event analyzed, the ballistics are released instantaneously and transit through 3 range gates in <10 s at radial velocities exceeding 40 m/s. The mass of centimeter- to decimeter-sized ballistics is confidently estimated at 0.5–7 tons. Contrastingly, the ash plume emission lasts several tens of seconds, exhibits lower along-beam velocities (<15 m/s in the radar direction) and longer transit times in the beam, depending on the wind speed and direction. Because the inferred mass becomes critically dependent on the assumed diameters for infra-centimeter particles, the ash plume mass is loosely constrained at 5.8×10^2 tons assuming an average diameter of 2 mm above the vent. The ability to remotely discriminate ballistics and ash plumes expelled simultaneously opens a way to better constrain the eruption mechanisms and source parameters. In particular, refining the mass fraction prone to be ejected in the atmosphere during large eruptions would help in the modeling and monitoring of tephra dispersal. Furthermore, inversion procedures to obtain numerical models matching the exact time-velocity distribution of the echo power in the observed signal, are the subject of ongoing research. These will enable the retrieval of initial eruptive parameters, such as initial gas velocities, particle size distribution, ejecta trajectories and exit velocities.

[13] **Acknowledgments.** The radar campaign was funded by the ACI Risques Naturels program of the French CNRS-INSU. Facilities for radar soundings were kindly provided by the Universidad de Costa Rica, ICE and Arenal National Park. We are indebted to M. Mora, G. Alvarado, C. Hervier, T.H. Druitt, M. Gouhier L.-F. Brenes, F. Arias and C. Ramirez for assistance in the field.

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