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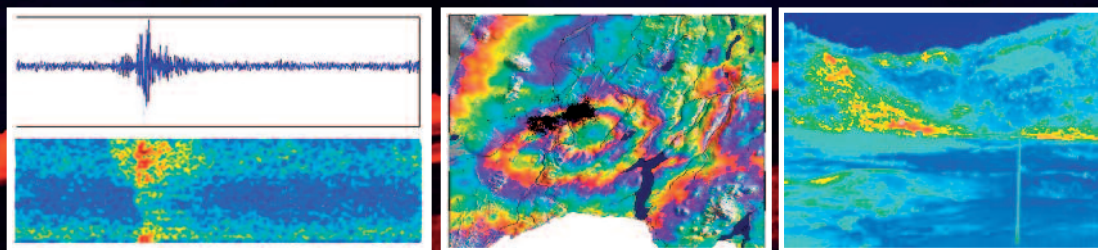
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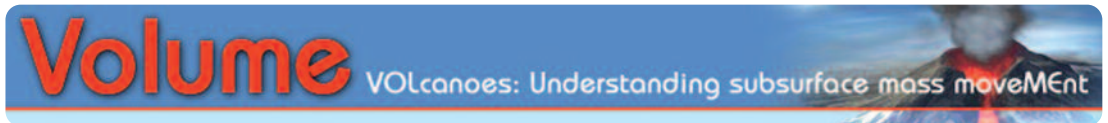
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## Joint seismic, acoustic and Doppler radar observations at Arenal Volcano, Costa Rica: Preliminary results

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### Abstract

Seismic, acoustic and Doppler radar data have been recorded at Arenal volcano since 2005. Detailed analyses of these data have been carried out by developing new software tools and applying high resolution time-frequency methods. Initial results reveal a complex relationship between radar, acoustic and seismic data, and provide new insights into Arenal's eruptive dynamics. New and interesting behaviors are observed, indicating important variations in eruptive activity through time. The understanding of those changes, and new seismic features recently observed, are some of the main goals for future work at Arenal volcano.

### Introduction

Arenal volcano is an andesitic stratovolcano, 1,730 m a.s.l. and 10 km<sup>3</sup> located in northwestern Costa Rica. Its formation began around 7,000 B.P. with the superposition of lava fields, pyroclastic and epiclastic deposits (Alvarado et al., 2003, Soto and Alvarado, 2006, Soto and Alvarado, 2008). Reactivation of this volcano occurred on July 29<sup>th</sup>, 1968 with a lateral explosive eruption. Since

then, it has been permanently active, characterised by almost constant lava extrusion, gas emissions, strombolian and vulcanian explosions and sporadic pyroclastic flows.

Arenal's volcanic activity is accompanied by a large variety of seismic signals including tremor, explosion quakes, long period (LP) events, rockfalls and volcano-tectonic (VT) events. Tremor is the most conspicuous signal and with two types occurring: (1) Spasmodic tremor that is characterised by energy with a frequency band usually in the range [1–6] Hz, and a spectra with no dominant peaks, and (2) harmonic tremor with the energy concentrated in narrow frequency bands that are integer multiples of the basic peak frequency that is generally in the range [0.9–2] Hz (Hagerty et al., 2000; Mora, 2003). The explosion quakes associated with Strombolian-Vulcanian activity have most of their energy concentrated in several peaks between 1 and 3 Hz. Strong explosions are often accompanied by a large audible boom (Alvarado and Barquero, 1987; Garcés et al., 1998); a high frequency seismic phase is produced several seconds after the P wave onset due to coupling between the acoustic waves and the ground. The explosion coda frequently becomes harmonic tremor (Barquero et al., 1992; Benoit and McNutt, 1997; Hagerty et al., 2000). LP events are very similar to explosions except that their records do not display acoustic phases. Therefore, there is probably no fundamental difference in their mechanisms.

The seismic sources of low frequency seismicity at Arenal are located below the active crater (Alvarado et al., 1997; Hagerty et al., 2000; Métaixian et al., 2002). However, the source mechanism is not yet well understood. Indeed, although several source models have been considered, none of them can account for all the spectral features observed, especially for tremor. Lesage et al. (2006) proposed the most recent attempt to explain spectral features of volcanic tremor at Arenal through a source model similar to the sound emission process of a clarinet. In this model, intermittent gas flow through fractures produces repetitive pressure pulses, whose period is stabilised by a feedback mechanism associated with standing or traveling waves in the magmatic

conduit. The pressure pulses generate acoustic waves in the atmosphere and act as excitation of the interface waves in the conduit. When the repeating period of the pulses is stable enough, they produce regularly spaced spectral peaks by the Dirac comb effect and hence harmonic tremor. When the period stability is lost, because of failures in the feedback mechanism, the tremor becomes spasmodic. Fractures in the solid or viscous layer capping the lava pool in the crater act as the clarinet reed, and the conduit filled with low velocity bubbly magma is equivalent to the pipe of the musical instrument. The frequency gliding is related to variations of the pressure in the conduit, which modify the gas fraction, the wave velocity, and possibly, the length of the resonator.

Recent multiparametric measurements carried out confirm the complex behavior, not only of the spectral characteristics of tremor, but also of the overall volcanic activity at Arenal and particularly the relationship between observed processes (explosions and degassing) and seismic, acoustic and Doppler radar signals. In this short paper we summarize the results of the preliminary processing of data obtained from 12 days of VOLDORAD 2 Doppler radar measurements carried out in February 2005 and almost two years of acoustic observations from 2005 to 2007. Both are combined with seismic observations. The Doppler radar enables the remote sounding of ash plumes, providing ejecta velocities and reflectivity, while seismic and acoustic records provide information on rapid mechanical processes and mass transfers in the magmatic conduit and at the magma-air interface. A full explanation of VOLDORAD principles can be found in Dubosclard et al. (2004), Donnadieu et al. (2005) and Gouhier and Donnadieu (2008). Acoustic and seismic observations were carried out at a site located 1.8 km west from the active crater with a Setra-270 pressure transducer and a permanent 30-sec GURALP CMG-6TD broadband seismometer.

## Results

### Doppler radar measurements

Initial radar data processing focused on correlations with seismic signals that can be associated with strombolian activity, sustained jets and passive ash emissions. To accomplish this, user friendly MATLAB-based software was developed to display the different data types on a unique graphical interface and extract the main features from both seismic and radar data.

The explosions, as seen by the Doppler radar and broadband stations, display a large variety of behaviours and features. For example, the seismic signal for the explosion of February 16<sup>th</sup>, 2005 at 15:22 contains two clear pulses at low frequency. The radar signal also displays a double pulse, with onsets delayed by 26 and 20 s with respect to the seismic first arrivals. They correspond to two short-lived jets separated by approximately 8s, with maximum velocities in the range 35-40 ms<sup>-1</sup>. However, for the explosion of February 16<sup>th</sup> 2005, at 15:46 the seismic record displays relatively large amplitude, but no radar signal is observed. Conversely, there are cases in which no seismic wave can be associated with a radar signal.

The volcanic tremor, either harmonic or spasmodic, as well as some emergent high-frequency (2-30 Hz) seismic events, is also sometimes accompanied by low level radar signals. This supports the theory that tremor at Arenal is related to the emission of ash-laden gas. For example, figure 1 shows the seismic record of an explosion followed by tremor. A first radar echo appears almost simultaneously with the seismic onset. However, about one hundred seconds later, another radar pulse is observed during the tremor episode. Repeated large amplitude oscillations are also observed in many cases, indicating staccato-like pressure released during the corresponding explosions.

The quantitative parameters extracted from the analysis of the seismic signals (energy, frequency content, duration, etc.) and from the radar measurements (power, maximum velocity, duration, and delay with respect to seismic arrival) are quite broad and poorly correlated with each other. This reflects the high variability of the explosion and tremor behavior of the volcano.

It is thus difficult to clearly define patterns of radar signals that can be associated to specific processes or seismic sources.

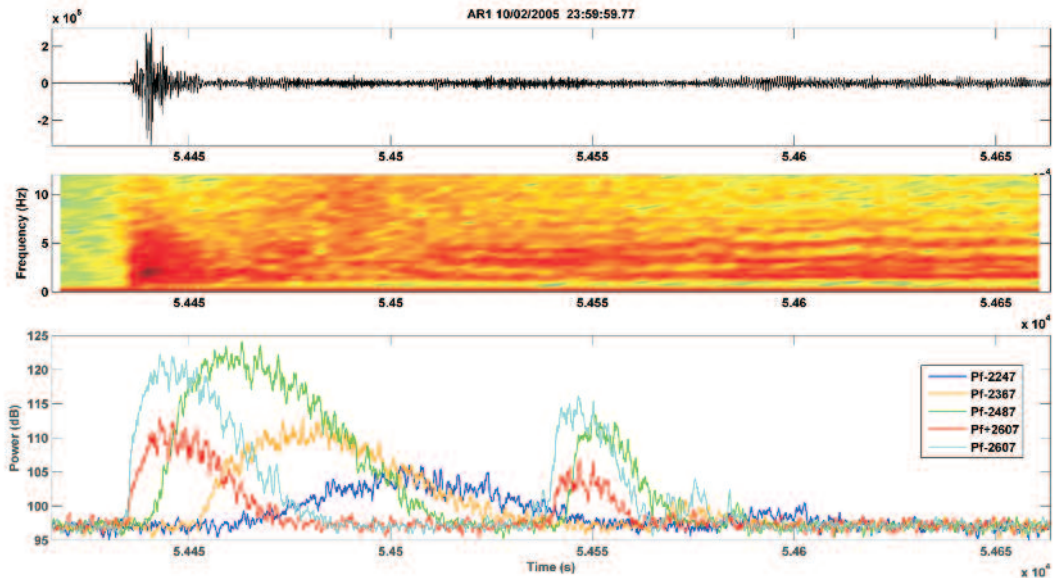


Figure 1. Explosive-tremor seismic event from Arenal volcano (above), its spectrogram (middle), and corresponding Doppler radar power in different gates (below).

### Acoustic measurements

Most of the acoustic events are associated with explosions recorded by broadband seismometers. Their waveforms include either a single short-duration pulse or a pulse followed by a slowly decaying coda lasting about ten seconds. Some series of acoustic events present very similar waveforms over a period of a few hours (figure 2a). This suggests that non destructive and stable source mechanisms can operate for hours to days.

At different time scales, event characteristics (waveform and spectra) can change providing evidence for changes on the source mechanisms (figure 2b). We calculated the amplitude, main frequency and delay of the seismic and acoustic signal associated with 50 explosive events. Figure 3 illustrates the relationship between the reduced energies of the acoustic and seismic signals. Although a roughly linear dependence appears between the two parameters,



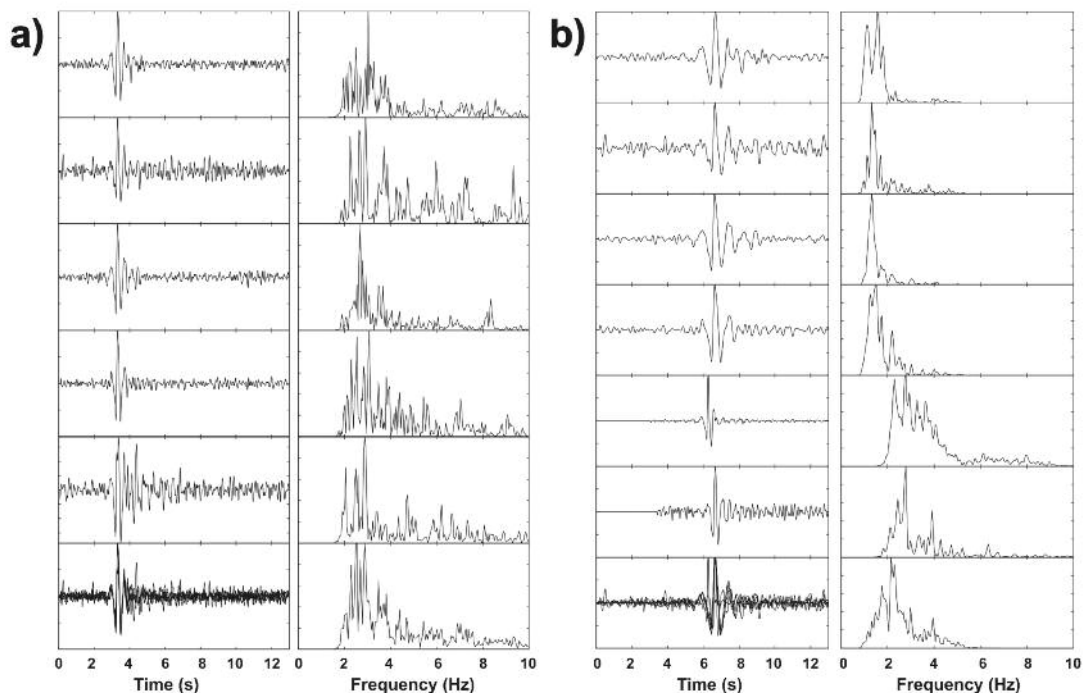


Figure 2. a) Acoustic signals associated to 5 explosive quakes on May 20<sup>th</sup>, 2005. b) Acoustic signals from May 20<sup>th</sup>, 2005 and two recorded in 2007 (last two). All signals were [0.5-10] Hz bandpass filtered, normalised and stacked (bottom). On the right, the corresponding normalised Fourier spectra are shown. For each group of signals the waveforms and geometrical mean spectra is shown at the bottom.

the relatively large dispersion of the points indicates that the energy partitioning of the acoustic and seismic energy may vary strongly. The mean time offset between the seismic and acoustic wave arrivals is about 4 s with values in the range [3 - 5] s.

When the acoustic noise level is low enough, long-lasting acoustic waves associated with harmonic tremor can be sometimes observed. In many cases, the spectral content of the acoustic and seismic records are quite similar (figure 4), which suggests that both types of waves have a common source mechanism. During some tremor, the acoustic records display series of individual short pulses with repetitive period of about one second.

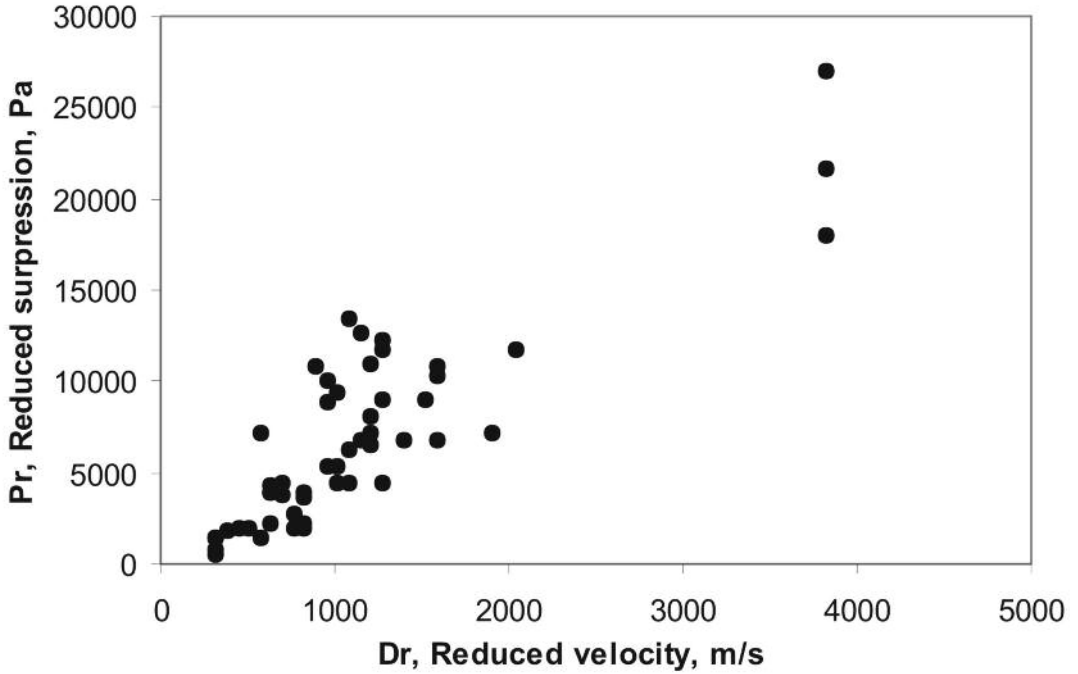


Figure 3. Energy partitioning between acoustic and seismic signals.

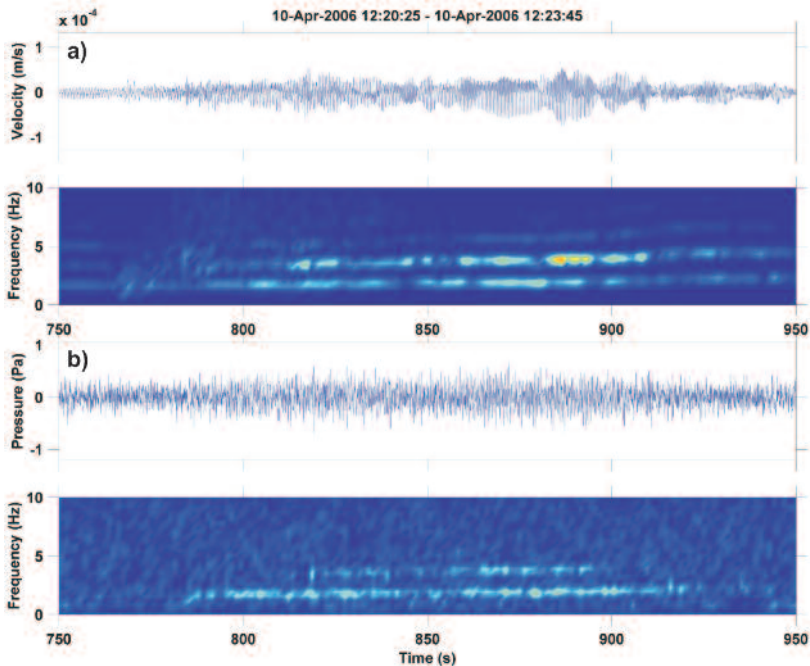


Figure 4. Harmonic tremor recorded on April 10<sup>th</sup>, 2006. The seismic (upper) and acoustic (lower) signals and corresponding spectrograms are shown.

## New seismic observations

Typically, Arenal volcano shows two types of tremor; harmonic and spasmodic. As identified by Lesage et al. (2006), both tremors can share the same source and can be observed depending on the state of the resonator. Close analysis of recent seismic records reveal a possible new type of volcanic tremor that can be produced by successive low frequency events that are very close in time. Their spectral features are similar to those of the spasmodic tremor and suggest a repetitive source.

## Conclusions

The seismic and explosive activity of Arenal recorded by the seismic, acoustic and radar sensors, displays a great variation in behaviour. Furthermore, the main features of the corresponding signals (energy, main frequency, delay, polarity) present high variability and relatively low level of correlation. Many mechanisms and phenomena may account for these observations: ash content of the gas (Johnson and Aster, 2005), vent geometry, source depth, gas content of the magma, multiple active vents, wind direction and speed, crater and dome-cone evolution, etc. Advances in the understanding of these processes will require multivariate analysis of larger numbers of events. Irrespective of this variability, the source mechanism may remain quite stable for a few hours or days, as revealed by the observation of families of similar acoustic events. Further work will focus on a systematic study of these similar events over long periods of recording.

Most of the observations presented in this paper are consistent with a source mechanism, for both the explosion and the tremor, which involves the opening of fractures due to overpressure and the emission of intermittent gases with variable ash content (Lesage et al., 2006). For both radar and acoustic measurements, the lack of video and meteorological data during the experiments makes it difficult to interpret the observations more precisely. Taking into account these parameters, new long-term continuous recordings of multiparametric data (seismic, acoustic, radar and others), and with visual or video observations of the active crater, would help constrain a more quantitative model of Arenal volcano system.

In the framework of the VOLUME project, new acoustic and deformation measurements were taken in 2008. In addition, new field campaigns have been carried out in December 2008 and January 2009, in which several dense arrays have been deployed together with Doppler radar and DOAS measurements. Final systematic analysis of seismic, acoustic and deformation data is in progress in order to complete the preliminary results presented in this work.

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