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Spectral analysis of harmonic tremor signals at Mt. Semeru volcano, Indonesia

Vera Schlindwein[1], Joachim Wassermann[2] and Frank Scherbaum

Institut für Allgemeine und Angewandte Geophysik, Ludwig-Maximilians-Universität München, München, FRG

Abstract. A detailed spectral analysis of tremor signals recorded at Mt. Semeru volcano, Indonesia, in October 1992 by the German-Indonesian Volcano Expedition (GIVE'92) reveals clearly harmonic spectra containing up to 11 integer harmonics. The spectral features can be explained by any rhythmically pulsating source producing a temporarily stable source signal. As one realisation of this concept we model the source as a resonating gas volume, generating seismic signals similar to the sound generated in a recorder.

Introduction

The origin of volcanic tremor has attracted considerable attention by seismologists. While most authors agree that the spectral characteristics of volcanic tremor - especially the stable narrow peaks with center frequencies which are independent of the recording site - are mainly due to a source effect [e.g., Aki et al., 1977; Chouet, 1988; Schick, 1992], a great variety of source models has been proposed:

Early studies considered free oscillations of magma chambers of different geometries as a possible generating mechanism of volcanic tremor [e.g., Shima, 1958; Shimozuru, 1961]. These models predict harmonic spectra consisting of equally spaced narrow peaks which, however, are generally not observed: tremor spectra typically show a single dominant peak or a non-harmonic sequence of peaks [Schick, 1992]. Difficulties also arise when estimating the dimension of the oscillating system necessary to generate the observed tremor periods. In the case of the tremor periods of Mt. Aso volcano (4-7 s [Sassa, 1935]), the dimensions of a spherical magma chamber are unreasonably large (2.5-4.9 km radius, assuming 1.0 km/s as the acoustic wave velocity of the magma).

Recently, a number of more complex source models for volcanic tremor have been proposed, including the resonance of a fluid-driven crack [Chouet, 1988], eigenvibrations of complex dike systems [Dahm, 1991], and unstable flow of a two-phase fluid [Martinelli, 1991]. These models are able to generate non-harmonic, peaked tremor spectra without requiring geologically unacceptable source dimensions, but none of them satisfactorily explains all of the observed characteristics of volcanic tremor.

In this study, we discuss the results of an analysis of volcanic tremor at Mt. Semeru volcano, Indonesia, revealing harmonic spectra with clear integer harmonics as high as order 11. In contrast to commonly observed tremor signals, this observation requires an explanation not for its complexity, but rather for its extraordinarily simple spectral structure.

Data Acquisition

Mount Semeru volcano, the highest mountain on Java, is situated in the eastern part of the chain of active volcanoes on Java (Fig. 1). Although Mt. Semeru has been continuously active for the past 25 years, it has only rarely been the subject of scientific investigations [e.g.: Fadeli and Budi, 1992]. In October 1992, the German-Indonesian Volcano Expedition (GIVE'92) [Hellweg et al., 1994] carried out seismic experiments in order to investigate the nature of Mt. Semeru's seismicity. A 3-component Lennartz LE3D 1Hz seismometer was operated in conjunction with a Lennartz MARS88 recording system along a profile from the summit to a distance of about 11.5 km (Fig. 2). Simultaneously, continuous recordings were made at a fixed location (base) approximately 7.5 km from the summit using a broadband 3-component Streckeisen STS2 seismometer coupled to a Geotech PDAS-100 data acquisition system.

In addition, the crater activity was observed during the campaign. The activity was dominated by frequent steam explosions and a variety of acoustic events, among which a regular pumping sound was the most striking feature.

The following data analysis is based mainly on the short-period dataset; seismic data from the continuous broadband recording and the observation of the crater activity provide useful supplementary information.

Data Analysis

Among other signals, the seismic data contain about 40 signals identified as harmonic tremor signals. A typical example is shown in Fig. 3. The signals begin gradually

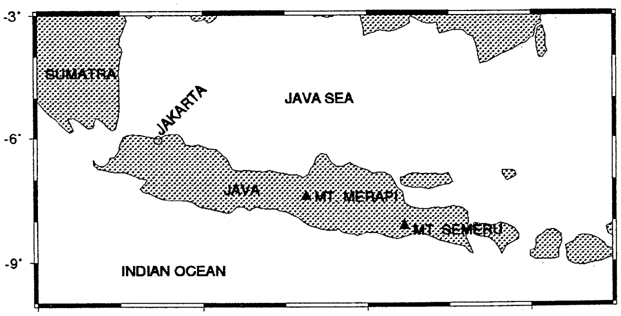

Figure 1: Location of Mt. Semeru volcano on eastern Java.

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[1] Now at AWI, Bremerhaven, FRG

[2] and Institut für Geophysik, Uni Stuttgart, Stuttgart, FRG

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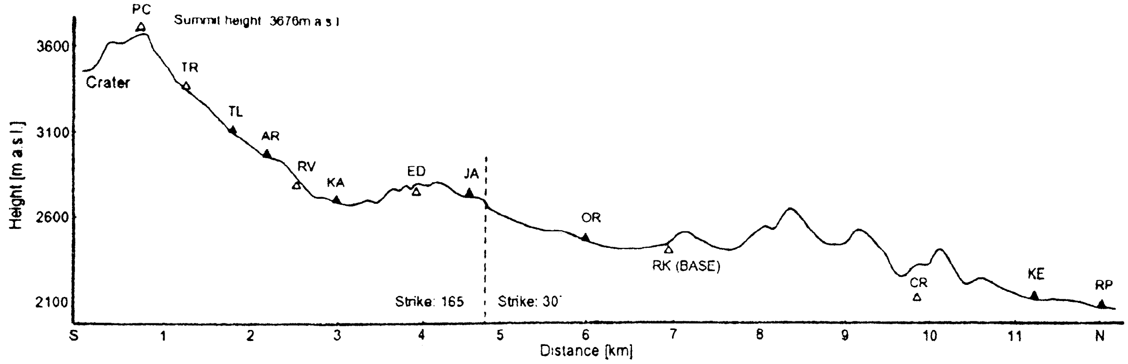

Figure 2: Sketch of a NS cross-section of Mt. Semeru (vertical exaggeration 2:1). Recording sites on the profile are marked by solid triangles, recordings sites off the profile with open triangles.

rather than abruptly and last between 40 s and about 1000 s. The envelope of the signals can often be described as spindle shaped, sometimes with a superimposed beating pattern. The enlarged section (Fig. 4) of a tremor signal clearly displays a repeating waveform which remains essentially unchanged during several cycles of the dominant tremor period.

The extraordinary character of Mt. Semeru's tremor signals is revealed in a detailed spectral analysis. Fast Fourier Transforms were calculated for successive 20 s time windows which overlap by 10 s. The spectral amplitudes are plotted as a function of frequency and time in Figs. 5 to 7. Typical tremor spectra can be characterised as follows:

1) The energy of the tremor signals is confined to a frequency interval between 0.5 Hz and 8.0 Hz and the spectra consist of strictly harmonic sequences of narrow peaks. The fundamental frequency in the range of 0.5 Hz to 1.7 Hz is accompanied by as many as 11 integer harmonics (Figs. 5, 6). On average, 4 to 6 pronounced peaks can be identified. The peaks appear for all seismometer components at the same frequencies, as can be seen from the spectrum in Fig. 3.

2) For close peak spacing (< 0.75 Hz) the fundamental mode is generally missing. Examples are shown in Figs. 5 and 6.

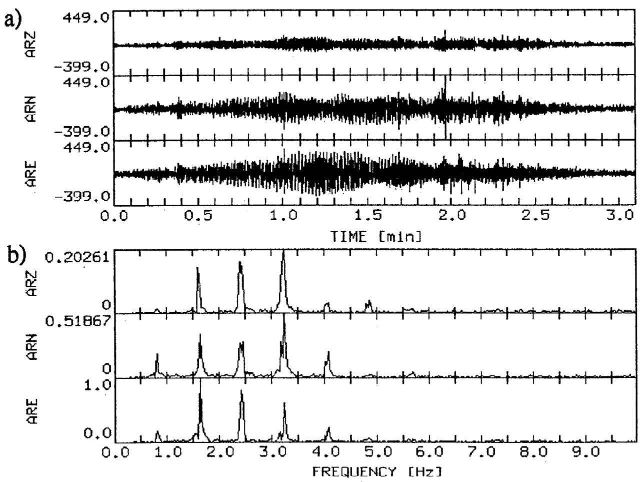

Figure 3: a) Harmonic tremor signal recorded at AR (cf. Fig. 2). The amplitudes are given in counts (1 count equals 80 nm/s in the passband of the seismometer). b) Amplitude spectrum (FFT) of the marked 30 s time window. The spectral amplitudes are normalized to the maximum value of the three components.

3) In three of the cases (e.g., Fig. 5), systematically lower spectral amplitudes of the even harmonics are observed.

4) Another distinct observation is that the frequency content of the tremor signals may vary in time. The peaks shift in unison towards lower or higher frequencies. The harmonic structure is maintained (Fig. 7).

5) In contrast to the simply-structured frequency content of the tremor signals, the spectral amplitudes of the peaks behave in a complicated way. They vary independently of each other and irregularly in space and time.

These results are confirmed by the reference recording at the base station. The tremor spectra of the broadband recordings exhibit the same characteristics. The fact that the peaks appear at the same frequencies and that shifts of the peaks occur simultaneously at both recording sites, strongly suggests that the structure of the harmonic tremor spectra is generated at the source.

Interpretation

Following the initial observations of harmonic tremor spectra at Sakurajima volcano [Kamo et al., 1977] and Langila volcano [Mori et al., 1989], the extraordinarily clear harmonic spectra observed at Mt. Semeru finally require an explanation for this phenomenon.

In theory, the basic features of the harmonic spectra can be modelled by a series of equally spaced spikes convolved with an arbitrary source signal, such as the time series shown in Fig. 8a with its spectrum:

1) The resulting spectrum consists of a fundamental frequency, defined by the time interval between the spikes, and its integer harmonics. The envelope of the spectrum is determined by the source spectrum (Fig. 8b).

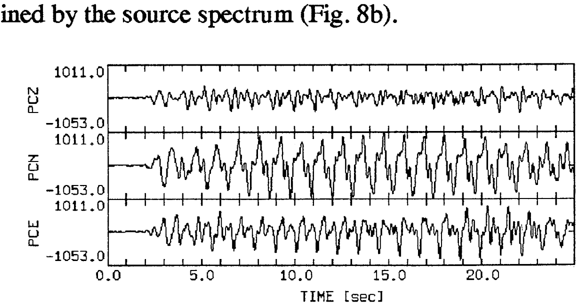

Figure 4: Harmonic tremor signal recorded at PC (cf. Fig. 2). The amplitudes are given in counts (1 count equals 80 nm/s in the passband of the seismometer). Note the almost unchanged waveform on the north component between seconds 5 and 20.

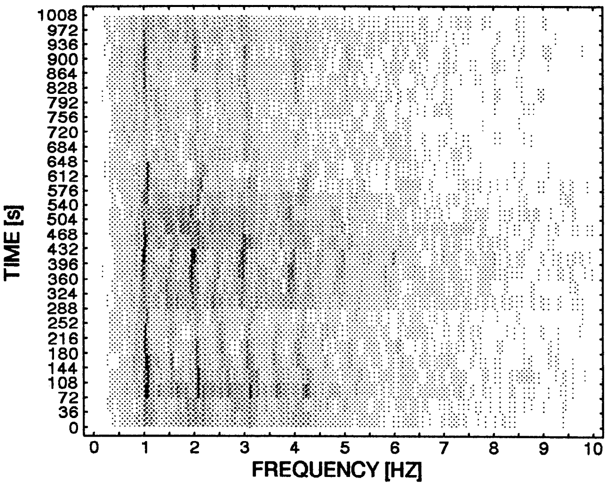

Figure 5: Time-dependent spectrum of the longest harmonic tremor signal recorded at AR (cf. Fig. 2). Due to the long signal duration, spectra were calculated from 40 s time windows overlapping by 4 s. The beginning of each time window is marked on the vertical axis. The signal shows 11 harmonics. Even harmonics have clearly reduced spectral amplitudes.

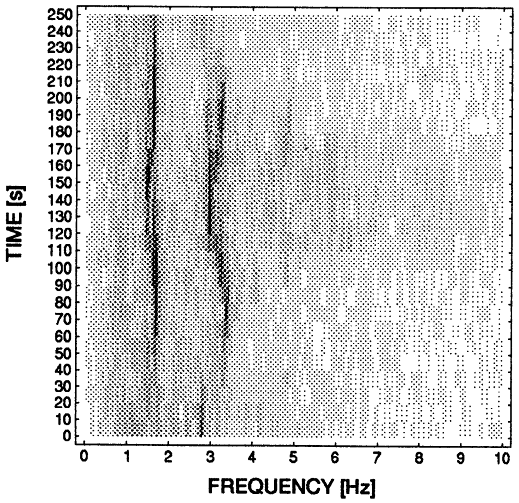

Figure 7: Time-dependent spectrum of a tremor signal recorded at AR (cf. Fig. 2). The beginning of each 20 s time window is marked on the vertical axis. The frequency variations of the spectral peaks are obvious. The peaks shift in unison, the harmonic structure is maintained throughout.

2) Changes in the time intervals between the spikes result in shifts of the spectral peaks.

3) Spectral amplitudes of the even harmonics are systematically reduced if a second spike series with lower amplitudes is shifted by half an interval and added to the original spike series.

Consequently, any seismic source radiating an arbitrary but temporarily stable source signal can explain the basic characteristics of Mt. Semeru's harmonic tremor spectra. In addition, from numerical tests, deviations of several percent from strict periodicity can be allowed to obtain harmonic spectra up to order 11. Furthermore, the observed temporal changes of the spectral amplitudes can be interpreted as time variations of the source signal.

One simple physical realisation of this generic model could be the free eigenvibrations of fluid or gas volumes as proposed e.g. by Shima [1958] or Shimozuru [1961]. Oscillations of a cylindrical gas volume closed at both ends represent a source signal which is intrinsically periodic. Its spectrum consists of a fundamental frequency, which is defined by the length of the cylinder and the acoustic wave velocity α of the gas, and its integer harmonics [Bergmann and Schäfer, 1990].

The generation of harmonic tremor signals at Mt. Semeru volcano could be modelled by oscillations of a gas-filled vertical dike bounded by a lava plug (which actually exists in the center of the crater) at the upper end and a magma column at the lower end. The maximum length of the dike (about 500 m) is calculated from the smallest fundamental frequency (0.5 Hz) and an order of magnitude estimate of the acoustic wave velocity in a hot gas (air at 400°C: $\alpha \approx 500$ m/s [Bergmann and Schäfer, 1990]). The observed shifting of spectral peaks would require rising or falling of the magma column at a maximum velocity of roughly 1.15 m/s.

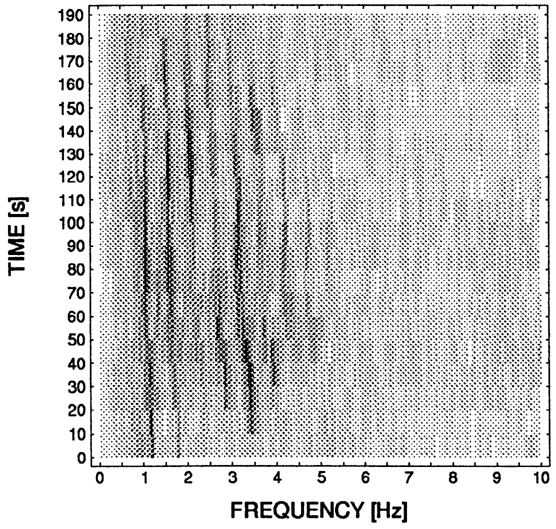

Figure 6: Time-dependent spectrum of a tremor signal recorded at AR (cf. Fig. 2). The beginning of each 20 s time window is marked on the vertical axis. 9 harmonics can clearly be identified. The fundamental mode is missing.

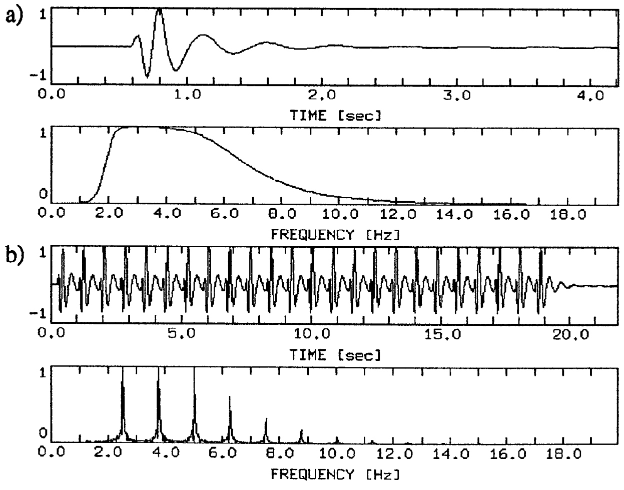

Figure 8: Rhythmically pulsating source. a) Seismic source signal and its amplitude spectrum. b) Periodic sequence of these source signals (cf. Fig. 4) and the resulting harmonic amplitude spectrum (cf. Fig. 3b).

Gas oscillations as a possible physical realisation of a rhythmically pulsating source at Mt. Semeru are supported by several arguments:

Primarily, the natural homogeneity of gas would allow an undisturbed development of perfectly harmonic oscillations. In addition, the gas volume itself would react passively to magma movement. Thus, the wavefield in the gas would not be severely disturbed by the volume change and its harmonic spectrum would be maintained during the frequency shifts.

Gas oscillations could be excited by degassing processes of the magma itself. Varying amplitudes of the tremor signals and a maximum signal duration of 1008 s suggest that the oscillations are produced by a continuous excitation mechanism. In analogy to the generation of sound in a recorder, we propose the following feedback mechanism: The pressure oscillations, once initiated by a pressure pulse caused by gas release from the magma, control in turn the degassing process. Missing fundamental modes at low frequencies in the harmonic tremor spectra, equivalent to overblowing of low tones in a recorder, are a typical phenomenon related to this kind of feedback mechanism [Bergmann and Schäfer, 1990].

At the upper end of the gas column, small amounts of gas could be pushed periodically through the lava plug by the pressure oscillations and produce the pumping sound which is heard in connection with harmonic tremor signals.

However, this simplistic model leaves several questions unanswered:

How can seismic waves be generated by the gas oscillations? Effective energy transmission between the compressional waves in the gas into the surrounding solid is restricted to the ends of the gas cylinder. The lava plug and the magma beneath the gas volume may be involved in the generation of the harmonic seismic waves, which considerably complicates a quantitative understanding of the process.

How realistic is a resonating gas volume of ≈500 m in dimension? How consistant is the presence of molten lava in the crater area, as is suggested by visual observations [Hellweg et al., 1994] with an oscillating gas body?

Conclusions

Using methods of spectral analysis, harmonic tremor signals recorded at Mt. Semeru were characterised. The tremor spectra consist of an unusually clear series of up to 12 evenly spaced peaks. Harmonic spectra of similar quality are rarely observed. The basic structure of the tremor spectra could be explained theoretically by a source which periodically radiates an arbitrary but temporarily stable source signal. As a physical realisation of this concept we proposed that the signals are generated by oscillations of a gas volume, which is bounded by magma at its lower end and by a lava plug at its top. While for example the excitation of gas oscillations could be explained in terms of this model, the generation of seismic waves by gas oscillations represents a general problem. An intensive survey of the crater activity (recording e.g. sound in a wide frequency range) combined with seismic array measurements (providing more detailed information on the radiated wave field) could give essential hints on the applicability of the proposed model to Mt. Semeru's harmonic tremor signals.

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V.Schlindwein, Alfred-Wegener-Institute for polar and marine research, Columbusstr., 27568 Bremerhaven, FRG, (e-mail: vschlind@awi-bremerhaven.de)

J. Wassermann, Institut für Allgemeine und Angewandte Geophysik, Theresienstr. 41/IV, 80333 München, FRG, (e-mail: jowa@flaucher.geophysik.uni-muenchen.de)

F. Scherbaum, Institut für Allgemeine und Angewandte Geophysik, Theresienstr. 41/IV, 80333 München, FRG, (e-mail: frank@bavaria.geophysik.uni-muenchen.de)

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