

VOLCANIC TREMOR OBSERVATIONS IN FOGO ISLAND, CAPE VERDE

Sandra HELENO¹, Susana CUSTÓDIO¹, Bruno FARIA^{1,2}, Zuleyka BANDOMO³

- 1) Núcleo de Engenharia Sísmica e Sismologia, ICIST, IST
- 2) Instituto Nacional de Meteorologia e Geofísica de Cabo Verde
- 3) Laboratório de Engenharia de Cabo Verde

ABSTRACT

We report observations of volcanic tremor (a sustained seismic signal characterized by well-defined peaks in the spectra) in Fogo Island, Cape Verde. Tremor in the range 2-3 Hz displays a semi-diurnal amplitude modulation controlled by the lunar tidal harmonic M2. High-frequency volcanic tremor, with spectral peaks in the band 6-21 Hz is also observed. Several occurrences are characterized by regularly spaced spectral peaks, but non-harmonic behavior is also common. The spatial variation of the amplitudes in Fogo and Brava islands suggests an offshore source of the high-frequency tremor, located to the SE of Fogo.

1. INTRODUCTION

Fogo Island, in the Cape Verde archipelago, is an active stratovolcano [1] whose last eruption occurred in 1995 [2,3]. Since 1999 a network of seismographic stations, both short-period and broadband (CMG-40T), have been in operation in Fogo and in neighbor Brava Island as part of a monitoring program [4]. Fig. 1 shows the location of 7 seismographic stations of the VIGIL network – additional instruments include four bi-axial tilt stations, a CO2 sensor and an automatic meteorological station.

Both volcanotectonic events (related with brittle fracture of rock) and long-period events (attributed to direct involvement of fluid in the seismic source) have been observed in the data collected so far. Volcanic tremor, a sustained seismic signal characterized by the absence of clear seismic phases in the seismogram and narrow, well-defined peaks in the spectra, is also a common observation. This signal is believed to be caused by fluid resonance inside the magmatic conduits [5].

This paper focuses on the occurrence of volcanic tremor. A particular type of tremor observed in Fogo displays a strong amplitude modulation at low (2-3 Hz) frequencies. A modulation by the lunar tidal harmonic M2 was recently proposed by Custódio and co-workers [6], whose work will be summarized here. High-frequency harmonic tremor, with spectral peaks in the band 5-25 Hz is also observed in Fogo. This observation is rare at other volcanoes: most reports from the literature point to lower frequencies (1 to 5 Hz). This probably results from the high seismic attenuation in volcanic areas, that acts as a filter for the higher frequencies. Preliminary results from the analysis of high-frequency tremor in Fogo will be presented in this paper.

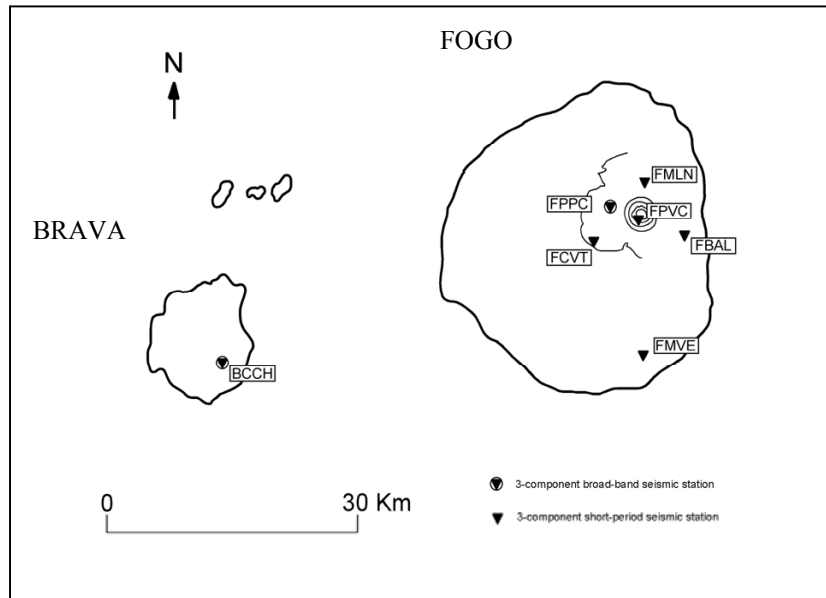


Figure 1: Seismic Network for monitoring Fogo and Brava Islands. FMLN: Fogo, Monte Losna; FPVC: Fogo, Pico do vulcão; FPPC: Fogo, Pé de Pico; FCVT: Fogo, Cova Tina; FBAL: Fogo, Baleia; FMVE: Fogo, Monte Vermelho; BCCH: Brava, Cachaço.

2. AMPLITUDE MODULATED LOW-FREQUENCY TREMOR

The dataset used in this study consists of 3-component records of seismic noise from five stations of the VIGIL network (FMVE, FMLN, FPVC, FPPC and BCCH, see fig. 1), digitized at 50 samples per second, and acquired over a period of 45 days in the summer of 2001. The data display a semi-diurnal amplitude modulation that is often strong enough to be detected by simple eye inspection of a sufficiently long record of the raw signal, as depicted in Figure 2. The modulation was strongest for stations FMLN and FMVE, but could be detected in all stations.

At least in some of the stations frequencies in the range 2Hz – 3Hz are selectively amplified. In order to understand the nature of the signal in this band, spectrograms of the data were analyzed, and spectral lines with time-varying intensity could be observed (fig. 3). We therefore interpret this part of the signal as amplitude-modulated volcanic tremor.

Next, the seismic traces were band-pass filtered from 1.5Hz to 7Hz with a 4-pole Butherworth filter using the SAC package [7], and the r.m.s. was computed on a moving window of 2 minutes and at time steps of 1 minute. In this way, a new time series was derived for each seismic trace, with a sampling rate of $f_s = 1440$ samples per day. A strong semi-diurnal periodicity of the r.m.s. time series was observed in all stations. The power spectral density of each r.m.s. time series shows a clear peak at 1.93 c.p.d., coincident with the frequency of the

lunar tidal harmonic M2. For each station, this peak is always strongest on the E-W component, and weakest on the vertical component.

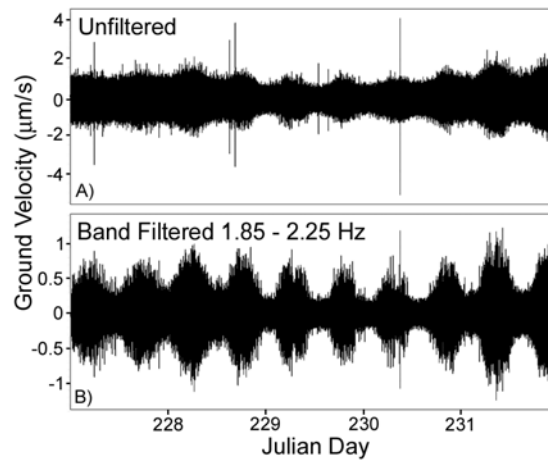


Figure 2: A) Five days of seismic noise at station FMLN, EW component, showing the semi-diurnal modulation of amplitude. B) Band-pass filtering the same noise sample between 1.85 Hz and 2.25 Hz enhances the modulation.

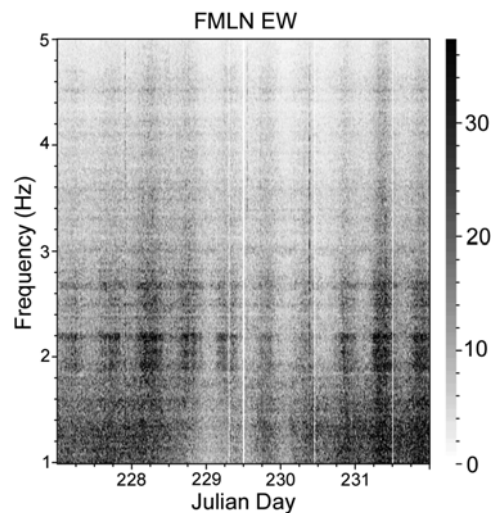


Figure 3: Spectrogram for the EW component of station FMLN, in the frequency range 1Hz – 5Hz and with the duration of 5 days. Besides the spectral lines, the background noise shows also a modulation with the same period. Similar patterns were also observed at station FMVE and, albeit in a less clear way, at FPVC.

In figure 4 we compare the spectra of the seismic r.m.s. time series with the spectrum of the synthetic tidal potential for the island, computed with the ETERNA 3.30 software [8], as well as the spectrum of ocean-tide data from Sal island, 220 km NE from Fogo [9].

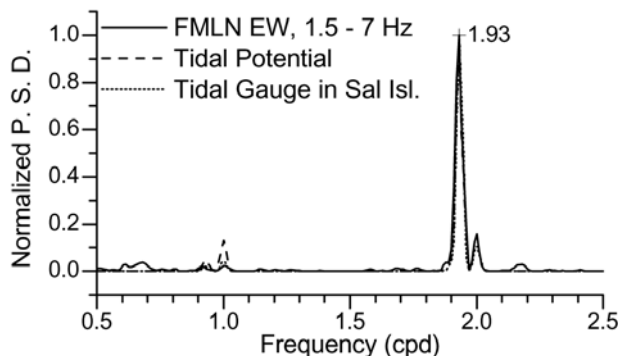


Figure 4: Normalized power spectral density of synthetic tide gravity potential (dashed), ocean-tide data from Sal Island (dotted) and seismic noise r.m.s. at station FMLN, EW component (solid).

The semi-diurnal peaks in the noise spectra have a clear similarity to the semi-diurnal peaks of the potential and the tide data. The good agreement in the frequency domain between the seismic r.m.s. series on one side, and synthetic tidal gravity potential and ocean-tide data on the other side, points to a tidal control on the seismic noise in Fogo.

Semi-diurnal periods are often found in environmental variables such as air temperature or air pressure, particularly in the tropics, and these may be reflected on the seismic noise thus leading to the erroneous inference of a tidal effect [10]. We computed the power spectral density of air pressure and air temperature records from the caldera in the Summer of 2001, coincident in time with the noise records, at a location within a few km from most stations (FMVE and BCCH are the most distant, at 15 km and 38 km respectively). The air pressure shows an important semi-diurnal periodicity, whereas air temperature shows mainly a diurnal modulation. In both cases the spectral peaks correspond to solar frequencies (1.00 c.p.d. and multiple), and therefore cannot explain the peak at 1.93 c.p.d. observed in the seismic modulation spectra.

3. HIGH-FREQUENCY HARMONIC TREMOR

For this study two different datasets were used, both consisting of 3-component records of volcanic seismic noise, digitized at 50 samples per second (with the exception of Brava station, at 100 sps). The first dataset contains data from all stations of VIGIL network (fig.1) and was acquired over a period of 5 months in 1999, from May 24 to October 11. During the second period of data acquisition, comprising 4.5 months in 2002 (from August 19 to December 30), four stations located inside Chã das Caldeiras contributed with data. This period coincided with a regional deployment of seismic stations in the Cape Verde archipelago, the CVULVZ network (G. Hellfrich, pers. com.), that also contributed data to this study.

During the period May-October 1999, we used the SAC package to compute discrete FFT's of the signal on non-overlapping windows of 2 minutes, for each station and component. These spectra were visually inspected and only episodes in which a particular spectral line was observed on at least two stations were selected for further analysis. The tremor episodes detected were practically always present at station FMLN, so for the purpose of tremor detection in the August-December 2002 period, only data from this station were analyzed. Program SCREAM was used to compute spectrograms on a moving window covering continuously the E-W component of station FMLN. The spectrograms were visually inspected, and when a spectral line was observed the other stations were checked for the same frequency. Again, only data with a spectral line recorded in at least two stations were considered for further analysis. Clearly the source was much more active during the May-October 1999 period, especially between mid-June and mid-July, when high-frequency tremor was observed almost every day. In contrast, during the August-December 2002 period, only one occurrence of tremor was recorded, in the beginning of November.

3.1. Spectral peaks

The observed frequencies span a spectrum from 6 Hz to 21 Hz: spectral lines at 7.2 Hz, 8 Hz, 8.9 Hz, 10 Hz, 10.9 Hz, 11.4 Hz, 11.6 Hz, 13.4 Hz, 14 Hz, 14.3 Hz, 15.5 Hz, 16 Hz, 17 Hz, 19.1 Hz, 20.3 Hz and 21 Hz were observed simultaneously on at least four stations of the network. In figure 5 an example of the recorded tremor is presented. The diagram represents a 30-minute length spectrogram of the vertical component of ground velocity recorded at FMVE station – a stronger line is observed at 13.5 Hz, and fainter ones appear at ~ 1.9 Hz intervals (11.6 Hz, 13.5 Hz, 15.4 Hz, 17.3 Hz, 19.3 Hz and 21.2 Hz). The area below 5 Hz is omitted, since it displays broadband noise only. FFT's of non-overlapping consecutive 2-min windows of this 30-min signal were computed to search for lower frequency spectral peaks, resulting on two other peaks at 9,6 Hz and 7,7 Hz, again at ~ 1.9 Hz intervals from the previous ones.

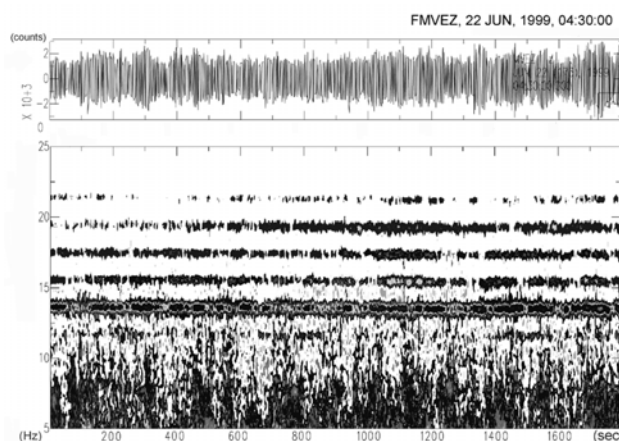


Figure 5: 30-minute spectrogram of the vertical component of ground velocity recorded at FMVE. The same signal was also recorded at stations FBAL, FMLN, FPPC and FCVT.

Figure 6 shows one of the FFT's computed, where the 7,7 Hz spectral peak can be seen. The amplitude of noise in the 0-6 Hz band is relatively low. This does not dismiss the existence of buried spectral peaks in that band, but makes the hypothesis of a tremor composed by a fundamental peak at around ~ 1.9 Hz followed by overtones very unlikely. No spectral peaks bellow 6 Hz were found in the dataset studied. The interval of ~ 1.9 Hz between spectral lines was not the only spacing observed. At some other times, clear non-harmonic behavior is also present, with random spacing between spectral peaks.

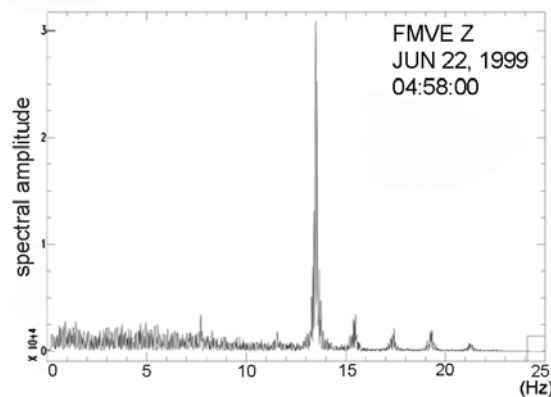


Figure 6: FFT of a 2-min window belonging to the previous signal.

3.2. Spatial variation of amplitudes

To study the variation of tremor amplitude between different stations of the network, we selected time intervals with spectral lines observed simultaneously on at least five stations. These consist of four 30-min intervals of data spanning the period June7-July13 and the frequency band 11-17 Hz. For each 30 min-interval, FFT's were computed for consecutive 2-min windows and the results were stacked to improve the signal to noise ratio. All intervals showed a similar pattern of inter-station amplitude variation, and in figure 7 we show one example of the stacking, which is representative of the different time intervals analyzed.

The highest amplitudes are recorded at Fogo coastal stations, FMVE and FBAL, situated at ~ 2 Km and ~ 1 Km from the sea. However, proximity to the sea is unlikely to be a determinant factor, since the station in Brava island, which is located 1,5 Km from the coast, records signals with amplitudes 8 to 25 times lower than FMVE and FBAL, and similar to the amplitudes recorded by FCVT and FPPC, located inside the caldera. Figure 8 illustrates the spatial variation of amplitudes recorded in Fogo and Brava.

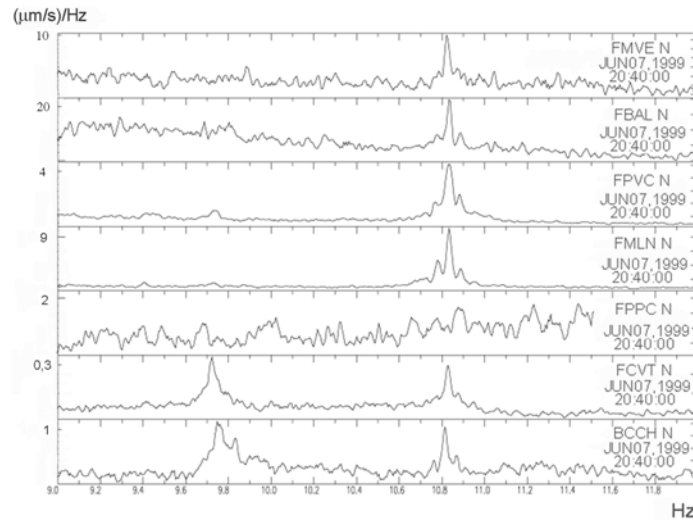


Figure 7: Stacking of 15 consecutive 2-min window FFT's (start time 20:40:00, Jun 07, 1999). With the exception of FPPC, all stations display a spectral peak at 10.8 Hz.

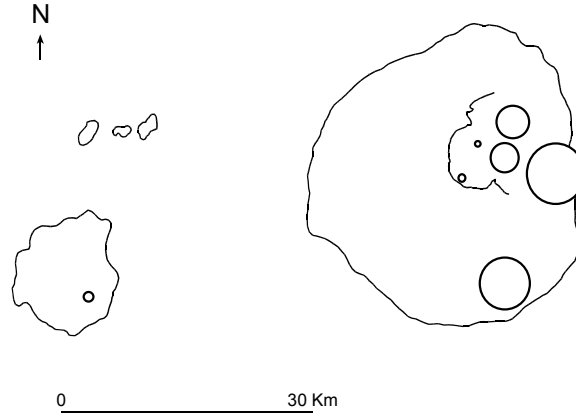


Figure 8: Spatial variation of mean normalized amplitude of two stacked spectral lines – 10.8 Hz, shown in the previous figure, and 15.5 Hz, obtained from stacking another group of 15 consecutive 2-min window FFT's (start time 02:40, Jun 16, 1999). Both spectral lines were recorded simultaneously on all 7 stations of VIGIL network.

3.3. Path and site effects

Site effects are unable to explain the spectral peaks observed, since the geology differs between recording sites: spectral lines were recorded simultaneously in seismic stations placed on top of ancient lavas alternating with consolidated piroclasts at FMVE and FCVT, unconsolidated lapilli and recent lavas at FMLN, and ignimbrites at BCCH. With the sole exception of station

FPVC, on top of Pico do Fogo, where the antenna mast is close to the seismometer, all stations were built far from trees, masts, cliffs or other possible sources of vibrations.

Path effects are also unlikely to be the cause of peaks in the tremor spectra since the source – station path is different for each seismic site: the distance between Fogo stations recording the same spectral peak at a given time reaches 15 km, and spectral lines were recorded simultaneously in Fogo and Brava Islands; also, stations that recorded the same spectral line are distributed all around the main eruptive center, Pico do Fogo, with drastic altitude variations between them (for example, 350 m at FBAL, 1800 m at FCVT and 2800 m at FPVC).

3.4. Non-volcanic alternative sources

Since the tremor observed in Fogo is stronger at the coastal stations, an offshore location for the source is a possibility, and biological or human-made sources from the sea should be investigated. Cultural noise is also higher in the littoral, where the main villages are located. Whales are known to produce low-frequency acoustic waves with overtones, that propagate through the ocean-sound channel. It is unlikely that the tremor signals were produced by whales since they contain spectral peaks bellow what is typically observed for even the largest whales ($>15\text{Hz}$), and have much longer duration than individual whale vocalizations ($<40\text{s}$) [11]. Vessel noise is a combination of narrowband tonal sounds at specific frequencies and broadband sounds. Large boats (over 50m) and ships create strong and lower-frequency sounds, with dominating tones up to $\sim 50\text{ Hz}$ [11]. Aircraft noise and power generators are other possible sources of tonal sounds. To test the possibility of vessel, aircraft or motor noise as the source of tremor, we placed a portable seismometer close to Fogo harbor, airports and power plants at the main villages, during a week-long experiment in the summer of 2003. Although some spectral lines were recorded locally at those sites, none was concomitantly observed on the permanent seismic stations in Fogo. It seems very unlikely that cultural noise onshore or vessel noise close to Fogo or Brava could be the cause of the widespread recorded tremor on these islands. We also investigated seismic noise spectra on the CVULVZ regional network stations, and found no spectral line observed simultaneously at more than one station. We therefore conclude that the tremor signal must be originated close to Fogo and Brava Islands. An electronic or processing-related cause was also discarded, since the tremor was recorded both by VIGIL network and CVULVZ stations on Fogo.

4. DISCUSSION AND CONCLUSIONS

The most unusual characteristic of the high-frequency tremor observed in Fogo is the fact that stations located several kilometers apart record the same high-frequency spectral lines, since volcanic media are known to attenuate strongly high-frequency seismic signals. However, the distribution of amplitudes in figure 8 doesn't suggest an unusual low attenuation in Fogo, instead it points to high attenuation of a strong signal. The source is probably shallow, or we wouldn't observe such drastic variations of amplitude between stations. Since the amplitude of tremor is higher in Fogo coastal stations and the signal is also observed in Brava island, an

offshore source is likely. The spatial distribution of amplitude shown in figure 8 suggests a location to the SE of Fogo Island.

Another feature of the high-frequency tremor is its complexity. We found no simple pattern of fundamental frequency followed by overtones, although regularly spaced spectral peaks are common. The spacing varies from occurrence to occurrence, and non-regular spaced peaks are also observed. A widely accepted model for generation of tremor is the *fluid-filled crack* [5], where the resonance of magmatic fluid or gas inside the crack results in radiated seismic energy characterized by narrow, well-defined peaks in the spectrum. Since the crack is modeled in 3 dimensions, a complex pattern of frequencies can appear, resulting from the interaction between the longitudinal and lateral modes of the source. For the example of tremor shown in figures 5 and 6, and for magma with low-concentration of gas as expected in Fogo, the *fluid-filled crack* model predicts a crack generating tremor with planar dimensions below 200m and thickness below 1m [12,13].

These dimensions are compatible with a shallow source, because such a small fracture would be closed by the hydrostatic pressure at depth. It is however puzzling that such a small, shallow source can produce sufficiently strong signals to be observed all over the island of Fogo. This possible contradiction is not addressed in this paper, and will be the subject of further investigation. We therefore suggest for the origin of the high-frequency tremor in Fogo and Brava a shallow submarine volcanic source, located to the SE of Fogo island, and consisting of a set of resonating fissures with dimensions of the order 200mx200mx1m.

The low-frequency (2-3Hz) tremor presented in fig. 3 was observed clearly in stations FMVE and FMLN, less clearly in FPVC and not observed in FPPC and BCCH (stations FCVT and FBAL were not in operation during this period). This pattern is compatible with the distribution of amplitudes seen in figure 8. This provides the only link between the two types of tremor observed, since the observations did not coincide in time in the datasets studied so far. Because the amplitude modulation of volcanic tremor implies a high sensitivity to changes of physical parameters inside the volcanic edifice, the investigation of the processes involved may provide a useful new tool for volcanic monitoring.

5. ACKNOWLEDGMENTS

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