Tidal modulation of seismic noise and volcanic tremor

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1. Introduction

In this paper, we present evidence of tidal modulation of seismic noise and volcanic tremor, derived from data recorded at Fogo Volcano (lat. 14.9°N; long. 24.3°W; Cape Verde Republic). Fogo is an active stratovolcano [Day et al., 1999] whose last eruption occurred in 1995 [Heleno et al., 1999]. Since 1999 a network of seismographic stations, both short-period and broadband, have been in operation in Fogo and in neighbor Brava Island as part of a monitoring program [Fonseca et al., 2003], and an automatic meteorological station is operated since 2001 in the volcano’s caldera. We used 3-component records of seismic noise from five stations (see Table 1 for instrument characteristics), digitized at 50 samples per second, acquired over a period of 47 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 1. This effect is strongest on the EW components of seismic records, which is usually the case for tidal tilt data [Melchior, 1983], and this raised our interest in investigating a possible link with the tides.

2. Data Processing and Analysis

As a first step, we analyzed samples of the seismic data corresponding to high noise amplitude and low noise amplitude separately. Details of the analysis are given in the legend of Figure 2, and the main results are: noise level in the range 1.5 Hz–7 Hz was amplified by 50% to 75% from low noise time-windows to high noise time-windows; in some stations, the amplification affected selectively certain frequencies; the central frequencies of these peaks are station-dependent, but stay in the range 2 Hz–3 Hz; these effects were clearest in the EW components.

Next, the seismic traces were band-pass filtered from 1.5Hz to 7Hz with a 4-pole Butterworth filter, 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 fs = 1440 samples per day and a length of 40 days (total duration of 47 days but with interruptions adding up to 7 days, with slight variations for some traces). Gaps due to operational problems in the acquisition were removed by linear interpolation, in order to minimize their impact on the spectral analysis. The relative importance of the modulation for the different stations and components is quantified by the histograms in Figure 1.

Figure 1. A) Five day long sample of seismic noise at station FMLN, EW component, showing the semi-diurnal modulation of amplitude. The power spectral densities given in this paper were derived from 40 day long time series. B) Band-pass filtering the same noise sample between 1.85 Hz and 2.25 Hz enhances the modulation.
In order to understand the nature of the spectral peaks, we analyzed spectrograms of the data. The raw records were decimated to 10 samples per second in order to allow the analysis of longer time series (due to computational limitations). In this way the frequencies were restricted to the interval 0–5Hz, but no spectral resolution was lost within that range. Figure 3 is a 5 days long sample of the spectrogram for the EW component of station FMLN, in the frequency range 1Hz–5Hz. Spectral lines with time-varying intensity can be observed, which we interpret as amplitude-modulated volcanic tremor [Chouet, 1988; McNutt, 1994]. Occurrences of tremor in Fogo volcano have been reported (albeit at higher frequencies, above 10Hz) with simultaneous recordings over the entire span of the seismic network [Heleno et al., 1999; Fonseca et al., 2003], and this spatial persistence is confirmed by the present data, suggesting spatially distributed or multiple hydrothermal sources. Besides the spectral lines, the background noise shows also a modulation with the same period. Similar patterns were also observed for station FMVE and, albeit in a less clear way, for FPVC.

The strong semi-diurnal periodicity of the r.m.s. time series is shown in Figure 4A for the three components of stations FMLN and in Figure 4B for the EW component of all other stations used. The power spectral density of each r.m.s. time series is also shown. The spectral resolution of the discrete Fourier transform is \( \Delta f = f_s / N = 0.022 \) cycles per day (c.p.d.), which is sufficient to resolve between the main lunar and solar semi-diurnal tidal harmonics (Table 2).
It is possible to identify in the spectra of Figure 4A 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 EW component, and weakest on the vertical component.

3. Environmental Data

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 [Neuberg, 2000]. In Figure 5 we present the power spectral density of air pressure and air temperature records from the caldera during the acquisition of the seismic data. 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.

4. Tides and Ocean Loading

We compare in Figure 6 the spectrum 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 [Wenzel, 1996], as well as the spectrum of the nearest ocean-tide data, recorded at Sal Island 220 km NE from Fogo (GLOSS database–University of Hawaii Sea Level Center). The semi-diurnal peaks in the noise spectra have a clear similarity to the semi-diurnal peaks of the potential and the tide data. A comparison in the time-domain requires the selection of a particular tidal time function to correlate with the seismic signal [Emter, 1997]. We performed a rough estimate by inspecting the cross-correlation between the seismic r.m.s. time series band-pass filtered around 1.93 c.p.d. and a) tide potential and b) tide gauge data, over the time span of the experiment. This revealed that the seismic modulation lags consistently about 90 minutes w.r.t. the tide potential, and that the ocean tide lags about 60 minutes w.r.t. the r.m.s.. While the former observation excludes dilatational strain due to the earth tide (which is in phase with the potential) as a candidate driving mechanism, the latter may indicate an indirect effect of the ocean tide through loading. However, the interpretation of the phase relation requires a careful...
modeling of ocean loading [Sherneck, 1991; Francis and Melchior, 1996].

5. Discussion

The formal spectral resolution of 0.022 c.p.d., in conjunction with the high signal to noise ratio of the seismic r.m.s. series, allowed us to identify the tidal component M2 and resolve it from the solar frequency of 2.0 c.p.d. We tested the effect of the data gaps on the spectra and concluded that it amounted to the introduction of low level noise and broadening of the tidal peaks, without significant loss of information (this reflects the fact that the gaps had randomly distributed onsets and variable durations). 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 (Figure 6), points to a tidal control on the seismic noise in Fogo. At least in some of the stations - FMLN, FMVE and maybe FPPC—frequencies in the range 2 Hz–3 Hz are selectively amplified, and we interpret this part of the signal as amplitude-modulated volcanic tremor.

Neuberg [2000] advises against using continuous noise and volcanic tremor data to identify tidal periodicities, on the grounds that these types of data are prone to environmental contamination. However, this obstacle was circumvented through the recording of air pressure and air temperature data close to the stations, which upon frequency analysis did not show the same tidal frequencies that were identified in the seismic data. The danger of periodic cultural noise in our data is minimum since Fogo Island is very underdeveloped. Further investigation of the processes involved in the reported amplitude modulation may provide a useful new tool for volcanic monitoring, but it requires a careful modeling of the ocean loading and other tidal effects.

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References


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Figure 5. Power spectral density of atmospheric pressure and air temperature at Fogo Volcano meteorological station, acquired simultaneously with the seismic data. Semi-diurnal peaks have a solar frequency of 2.00 cycles per day, and therefore cannot explain the modulation at 1.93 c.p.d.

Figure 6. 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).