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Microseism and Volcanic Tremors: Two examples of Non-Linear Resonances

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DINAMICS
OF
MICROSEIM TIME SERIES

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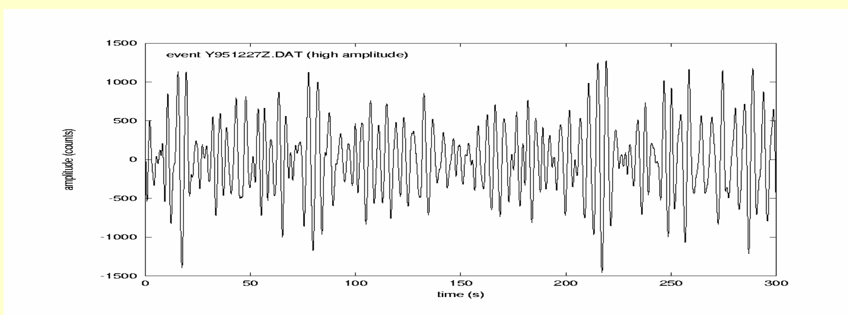

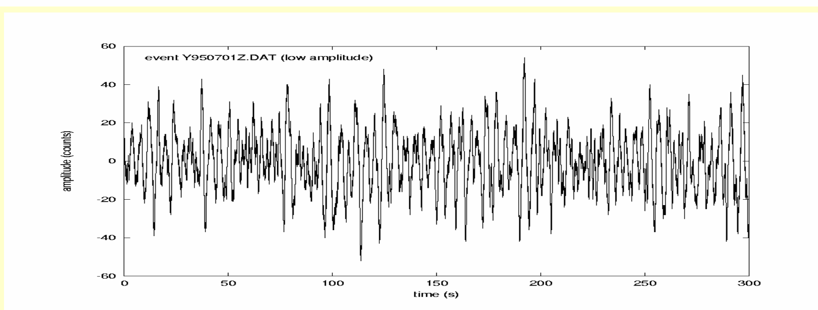

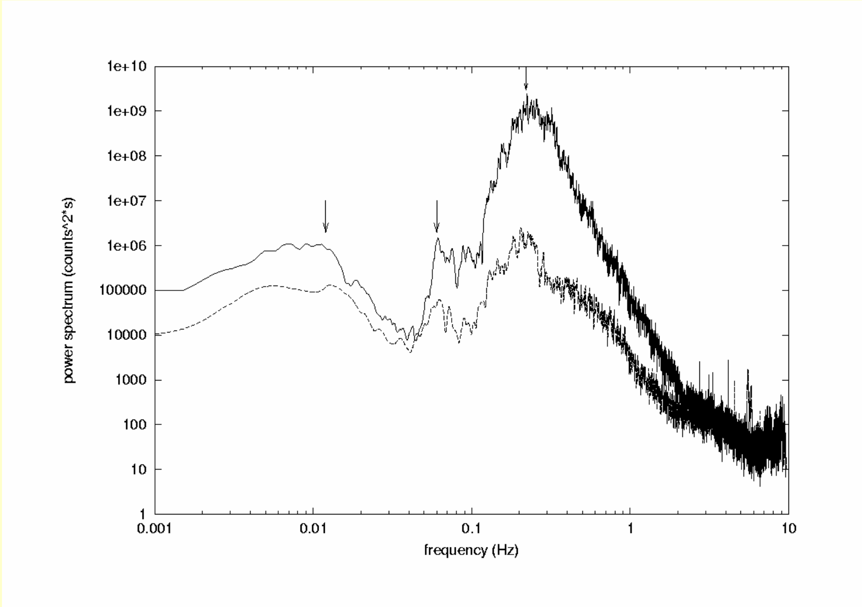

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MAIN FEATURES OF MICROSEISM TIME SERIES

- **Time domain**: modulated signals defining two wave-packets
  - ~ 70 s
  - ~ 17 s

  each one composed of oscillations of ~ 5 s.
- **Frequency domain**:
  - Secondary peak ~ 0.20 Hz → 5 s period osc.
  - Primary peak ~ 0.07 Hz → 17 s wave-packet
  - Gravity peak ~ 0.016 Hz → 70 s wave-packet

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INLAND OBSERVATIONS

- The central frequency of the main spectral peak may suffer slight variations, due either to variations of the source or to the receiver structure.
- Up to 1 Hz the spectral shape is preserved, irrespective of the strength of the atmospheric activity. At higher frequencies all spectra coalesce.
- Microseism propagate incoherently.
- The most widely accepted model for the origin of microseisms is that of Longuet-Higgins, a stationary vertical oceanic wave acting upon the seabed: an external *harmonic force*.

TIME SERIES ANALYSIS

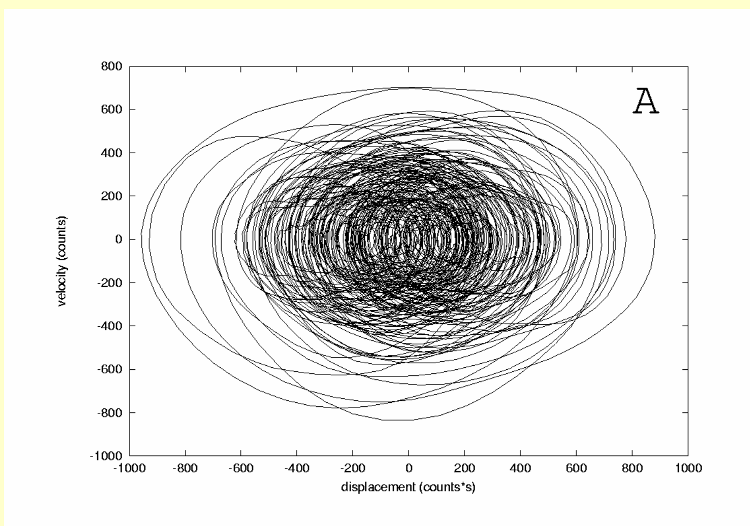
An analysis of the microseism time series reveals that they are:

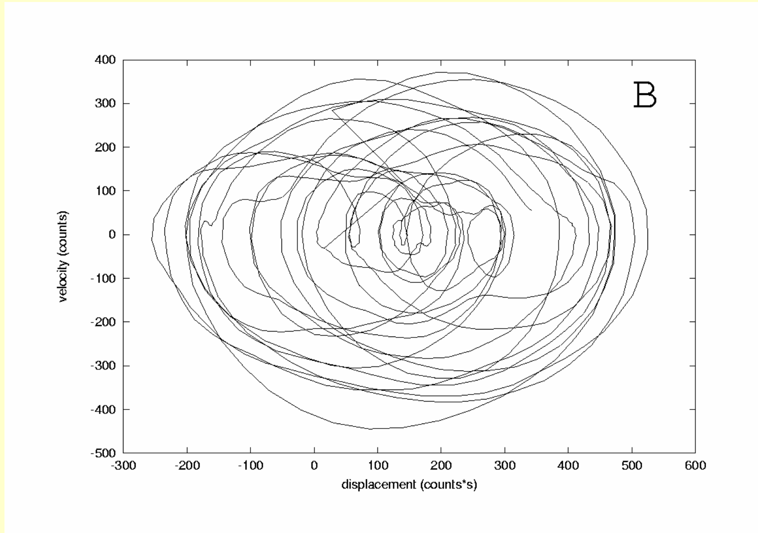
- Non-stationary
- Stochastic
- Non-linear

PHASE PORTRAIT

A plot of velocity ground motion (as recorded by a broad-band station) *versus* displacement (obtained by numerical integration) displays a complex structure of the motion in phase space. This motion follows well defined trajectories, similar to those of a particle bouncing irregularly in a potential well, consisting on a superposition of loops of different mean radius (*i.e.*, motions with different frequencies) with the center of the loops displaying separate irregular oscillations over a well defined path. The corresponding motion is random in the sense that it is not possible to predict neither the evolution of the center of the loops, nor its mean radius.

NEED OF A MODEL TO INTERPRET SEISMIC RECORDS AND MAIN FEATURES





MICROSEISMS' PHENOMENOLOGICAL MODEL

(Correig & Urquizu, 2002)

$$\dot{q} = p$$

$$\dot{p} + \frac{\partial V_0(q)}{\partial q} + \delta p = \Sigma_{i=1}^{2} \gamma_i \cos(\omega_i t) + \varepsilon F(t)$$

$$V_0(q) = -\alpha \frac{q^2}{2} + \beta \frac{q^4}{4}$$

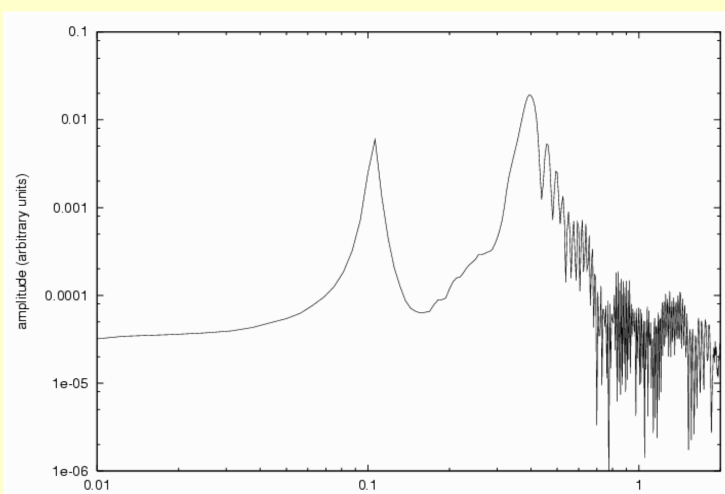
$$\alpha = \alpha_0 + \eta f(t)$$

The potential V_0 has the meaning of medium response

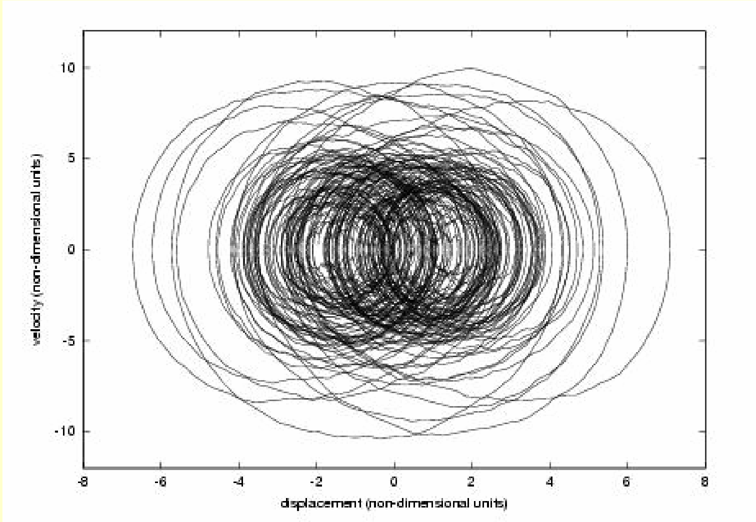
MEDIUM RESPONSE

We should emphasize that the potential $\mathbf{V_{ms}}$, representative of the medium structure, is a **global property**, not a local one. As a consequence, this potential will be representative of the whole structure. On the other hand, the whole structure may suffer fluctuations as a function of the position, a **local property**. These fluctuations will thus be representative of the local structure, known as **site effect**.

NUMERICAL SIMULATION - 1



NUMERICAL SIMULATION - 2



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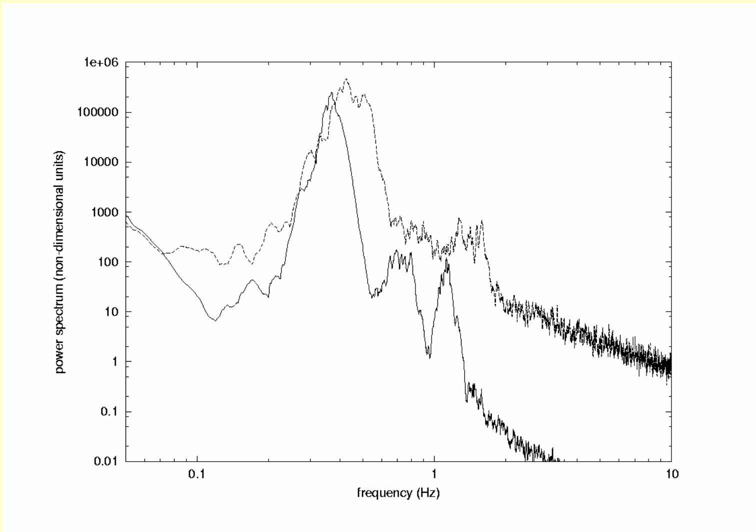

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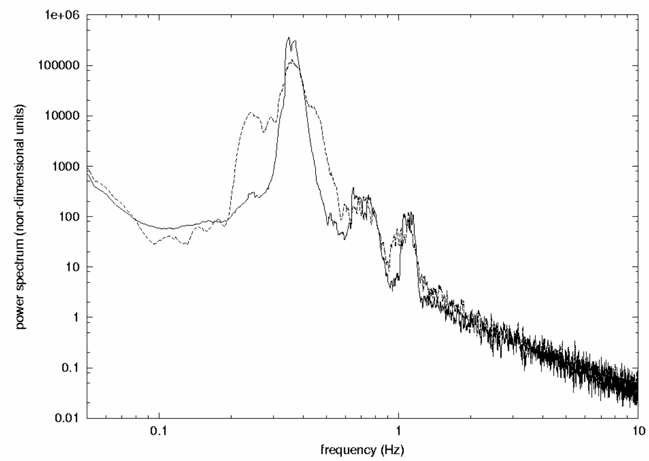

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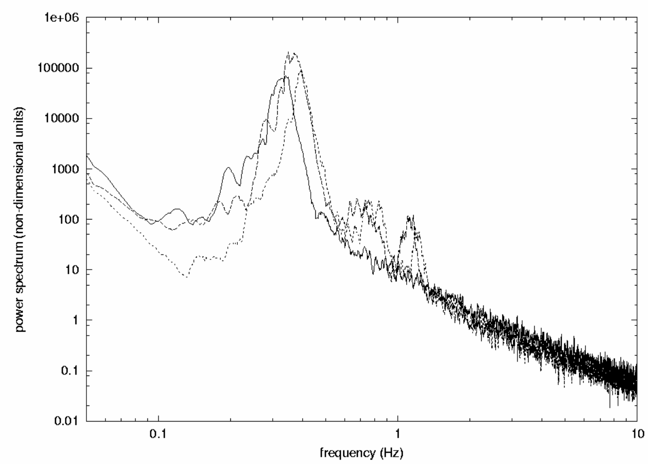

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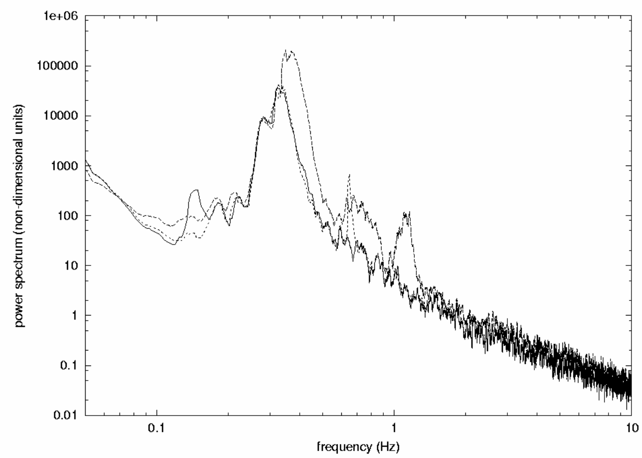

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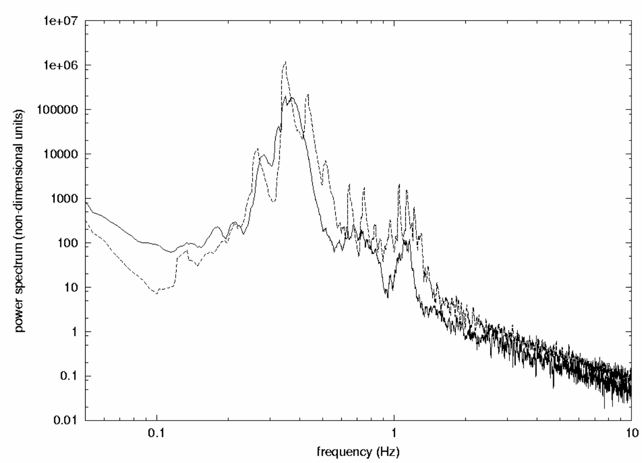

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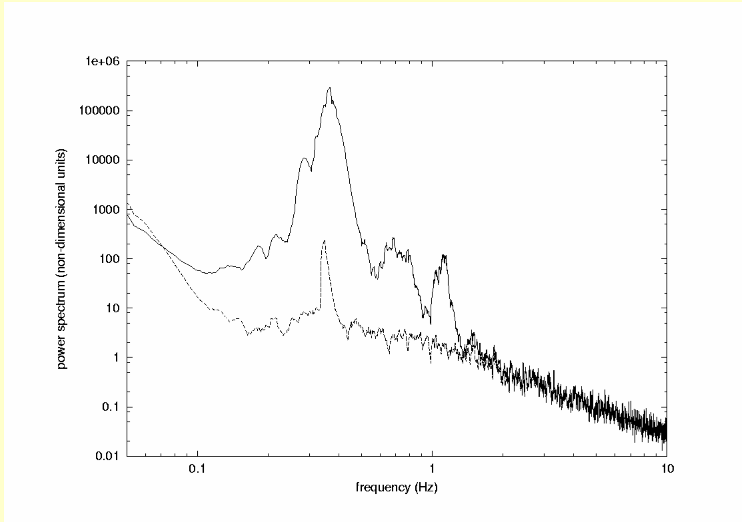
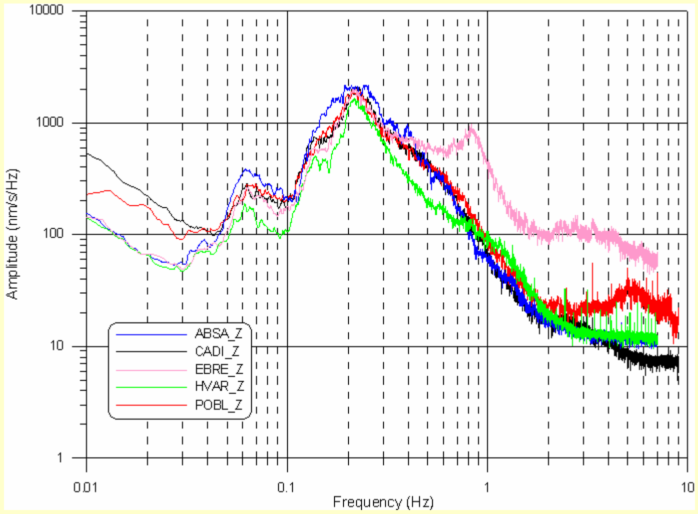


Influence of the model parameters on the spectral features

Effects on	**δ**	**α_0**	**η**	**β**	**γ_2**	**f_2**	**ε**
Resonant peak		x					
Broadening			x			x	x
Amplitude	x			x			
Shifting				x			x
Subharmonics			x		x	x	x

MINIMUM SPECTRA



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MINIMUM SPECTRUM: THE EQUIVALENT OF THE BLACKBODY RADIATION?

- For the **minimum spectrum**, the source of energy would be that remaining after the main transient contributions, atmospheric and oceanic, are suppressed, *i.e.,* fluctuations at all scales.
- This situation is formally similar to the **blackbody radiation in a cavity**: for a given temperature, each mode (frequency of light) has a given energy. Once the thermal equilibrium is reached, the spectrum of radiation has the shape given by Plank's law.
- One interesting feature is that the shape of the spectrum is **independent of the geometry** of the cavity.
- In the microseism spectrum, the equivalent of the temperature would be the stress, and the shape of the spectrum at the "stress equilibrium" would be approximated by the minimum spectrum, known as the **Base Level Noise Spectrum**.

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RELATED STUDIES

Low frequency band

- In 1998, several seismology groups in Japan and in the US detected a background *hum* at the free oscillations frequency band, and demonstrate that these oscillations are excited even during aseismic periods. It is hypothesized that its origin r3elay on the coupling between the Earth and the atmosphere.
- Gross (2000) has shown that a possible mechanism for the exitation of the Chandler wooble (a resonance of the Earth's rotation with a 14 months period) may consist by a combination of atmospheric and oceanic processes, with the dominant excitation mechanism being ocean bottom pressure fluctuations.

High frequency band

- At frequencies higher than 1 Hz the hum consists in random resonant oscillations, generated by local meteorological activity (of random nature) plus cultural activities.

CONCLUSIONS

By similarity with the oscillatory model, we hypothesize:

- The primary peak of microseism spectra can be interpreted in terms of the resonant response of the Earth's crust and mantle.
- The secondary peak, when present, can be interpreted as a subharmonic of the primary peak.
- The randomness of microseism phase spectra can be due to medium lateral variations and to local, high-frequency, random 'noise' (local meteorological conditions and cultural activity) through an inverse cascade process.
- Microseim activity, as a resonant (stochastic) response of the mantle lies between the high frequency local response of the medium (random) and the (linear) free oscillations low frequency response of the whole Earth.

Nonlinear Modeling of the Base Level Noise Spectra in Broadband Stations

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Abstract

In this work a comparison of the behaviour of noise in five broadband stations, located in different geological units, has been performed. A spectral analysis of the microseism, using the continuous recording in time series 30 minutes length, has been carried out to determine its characteristics. The base level noise spectrum in has been obtained by scanning the full set of computed spectra corresponding to several years of recording in continuous mode. The comparison of the resulting spectra for the diverse stations reveals a high level of similarity. On the one hand, there is a great coincidence in the values of amplitude in the frequency band 0.03 Hz - 1.0 Hz and, on the other hand, the resulting spectra show the classical shape being characterized by the primary and secondary frequency peaks. These peaks occur at the same frequency for all studied seismic stations and present a ratio of 1:3 instead of the widely reported ratio 1:2. This 1:3 ratio may be an indication of its structural origin, in good agreement with a recent theoretical model based on the response of a nonlinear, damped, forced oscillator. According to the model, the base level noise spectrum can be interpreted as the resonant response of the solid Earth to atmospheric and oceanic activities.

Key words: seismic noise, base level noise, nonlinear modeling, resonances

AGU index terms: 7260 (Theory and modeling), 7299 (General)

1 Introduction

From the installation of the first seismic stations, it has been widely observed that, in the absence of earthquakes, the seismic records display the presence of a continuous ground motion, of variable amplitude. It is today well established that this permanent activity is due to the combined activities of atmospheric and oceanic as well as human activities. Usually this continuous activity is known as *microseism* or *seismic noise*, the last because it masks the arrival time of the transients of interest, *i.e.* the seismic waves generated by earthquakes. As a consequence, a lot of work has been carried out for a correct determination of the noise levels (the maximum and the minimum) of the seismic stations in order to know the detectability (*i.e.* the capability of detection of the transients of interest) at a given place as well as to its origin and propagation. As representative references we may highlight Peterson (1993) and Webb (1998), and references therein.

However, another interpretation of the microseism activity, instead of that of 'annoying noise', is possible: we can turn the sentence and say that *noise is the signal*. This new interpretation follows after the discovery by Nawa *et al.* (1998) of the incessant exciteation of the Earth's free oscillations in quite places and in the absence of earthquakes. Following this point of view, Correig and Urquizú (2002) and Ryabov et al (2003) analyzed microseism time series as recorded at the broadband seismic station of CADI (Eastern Pyrenees, Spain) from the point of view of dynamical systems. Previous analysis of the data were carried out by Vila (1998) and Vila and Macià (2002). Correig and Urquizú (2002) deduced a phenomenological model able to explain the main features of the observations of Vila (1998) and Vila and Macià (2002).

A close inspection of the time variation of the 30 minutes long time series spectra, of the six years of continuous data recorded at CADI station, reveals (Macià and Vila, 2002), apart of the well known daily and seasonal variations, other variations presumably associated to local and regional atmospheric activity, very difficult to simulate numerically, that could be considered as fluctuations about a mean reference spectrum.

The aim of the present study is to find this mean reference spectrum, that we have termed the Base Level Noise Spectrum (BLNS), and attempt its explanation in terms of dynamical systems through the phenomenological model derived by Correig and Urquizú (2002). As will be explained later on, the BLNS will simply correspond to the minimum of each spectral component of the seismic spectra, with the underlying assumption that the external forces will be minimized. This process will be repeated for different seismic stations located in different geological units, to get some insight on the possible universality of the BLNS. The plan of the paper is as follows: Section 2 will deal with the procedure to obtain the Base Level Seismic Noise and its application to five different seismic stations. In section 3 a possible dynamical interpretation of the BLNS is provided, and Section 4 is devoted to the discussion and conclusions.

2 The Base Level Noise Spectrum

To determine the BLNS of a seismic station, we have computed the Fourier spectra from the continuous recording in segments of 30 minutes length for a period of time not shorter than a year. This minimum interval has been determined from the analysis carried out at CADI station (Vila, and Macià, 2002), which clearly showed it was a accurate enough to include the maximum and minimum microseism activity representative of a given location site, although in the present work we are only interested in the minimum. Of course, as more data is analyzed, more accuracy can be reached. Note that, as we are only interested in the minimum, there is no need to previously determine the seismic activity, that should be removed in the case looking for the maximum activity. In computing the spectrum, for each 30 minute interval, the mean and the linear trend has been removed from the raw data, which has also been corrected for instrumental response.

The BLNS has been computed for the five broad-band seismic stations ABSA, EBRE and HVAR (MIDSEA -Mantle Investigation of the Deep Structure between Europe and Africa-, ETH, Zürich), CADI (IEC -Institut d'Estudis Catalans, Barcelona) and POBL (MIDSEA and IEC). Details about the stations and time intervals used are presented in Figure 1 and Table 1.

Figure 2 display the BLNS for the three components of CADI station. CADI station has been considered as the reference station because of its larger interval of recorded data (6 years), see Table 1. It is notorious the high degree of similarity among the BLNS of the three components, as well as the similarity in its amplitudes and the same well defined spectral peaks, all centered at the same frequencies. Figure 3 presents the BLNS for the vertical component of CADI station for each one of the 6 years: it can clearly be seen that, except for minor fluctuations all spectra coalesce to the same structure from 0.04 Hz to 1.0 Hz; some minor differences appear at frequencies lower than 0.04 Hz. In Figure 4 we present the BLNS for the vertical component of the remaining 4 stations. Clearly, the shape of the spectra is the same for all stations and intervals of time for the frequency range 0.04 Hz - 1.0 Hz, except for in EBRE station, for which there is a significative departure from 0.3 Hz to 0.7 Hz (probably due to resonant effects of the Ebro basin). Figure 5 is a comparison of the BLNS for the five stations. It is surprising the coincidence of the shape and amplitudes from 0.05 Hz to 0.3 Hz (the interval of the microseism activity). The discrepancies at lower frequencies may be due to other effects not accounted for, and at higher frequencies in terms of local site effects.

An important feature of Figure 5 is that the BLNS of the five stations display the same above mentioned spectral characteristics: a main peak located at 0.21 Hz and a secondary peak located at 0.07 Hz. Usually, these peaks are referred to as primary peak (0.07 Hz) and secondary peak (0.21 Hz) in the classical literature on microseims. There is, however, an important difference with respect to the classical interpretation: whereas the frequency of the primary and secondary peaks are in the proportion 1:2, from Figure 5 it can clearly be seen that the proportion of the lower (0.07 Hz) to the higher (0.21 Hz) peak is 1:3. It may be argued the existence of a third peak, or at least an inflexion in the slope of the curve, located at 0.13 Hz. This feature is not present at station ABSA, although it could be due to an insufficient number of data: indeed we have observed the narrowing of this upper part (remaining fixed the lower part) as the interval of data analyzed increases, in the sense that we are reaching lower amplitude values. It thus turns out that the wideness of the main peak, or, in other words, the frequency contents of the signal, is dependent on the amplitude, thus revealing nonlinearity. It seems, thus, that the main peak is composed of two regions: a lower one with constant slope (that is, independent of the amplitude), and the upper one, dependent on the amplitude. When the minimum spectrum is reached, both regions are well separated by a sharp change in slope, apparently defining a new peak. These characteristics were already present in Correig and Urquizú (2002), although not recognized at the time. If this feature is confirmed, the lower frequency peak (0.07 Hz) and this one (0.13 Hz) would be approximately in the proportion 1:2.

The difference in the proportion of the two peaks, 1:2 in the classical interpretation, and 1:3 as revealed from the BLNS, may have important consequences when attempting to interpret its meaning. It is widely assumed that the two peaks are due to ocean waves (Aki and Richards, 1980). The smaller occurs at the primary frequency to witch most ocean waves are observed, and is considered to be due to the action of ocean waves on coasts, and the main peak was explained by Longuet-Higgins (1950) as due to the pressure from standing ocean waves which may be formed by waves traveling in opposite directions in the source region of a storm or near the coast. This mechanism generates seismic waves with a frequency twice of that of ocean waves, hence the proportion 1:2 between the two peaks. From the observational point of view, this proportion is only approximate and subject to strong fluctuations due to weather conditions. On the other hand, when deducing the BLNS the influence of the weather conditions are minimal, its shape is very robust and its central frequency is very stable, so that we are confident on the stability of the proportion 1:3. That rises questions on the validity of the classical interpretation of microseisms as being originated by ocean waves.

In the following we will look for an explanation of the features of the microseism time series by means of a phenomenological model (Correig and Urquizú, 2002).

3 Nonlinear modeling of the BLNS

In a previous paper, Correig and Urquizú (2002) showed that microseism time series are nonlinear, non stationary and stochastic, and constructed a phenomenological model able to reproduce these three main features as well as the motion in phase space and spectral characteristics. The model, that can be considered as an extension of the Duffing equation, reads

$$
\begin{aligned}
\dot{q} &= p \\
\dot{p} + \frac{\partial V(q)}{\partial q} + \delta p &= \sum_{i=1}^{2} \gamma_i \cos(\omega_i t) + \varepsilon F(t)
\end{aligned}
\tag{1}
$$

where V is the bistable potential defined as

$$V_0 = -\alpha\frac{q^2}{2} + \beta\frac{q^4}{4} \tag{2}$$

and $F(t)$ is random noise. δ is the coefficient of damping, β the coefficient of nonlinearity, γ_i the amplitudes of the external harmonic forces of frequency ω_i and ε the noise amplitude. In order to reproduce the spectral shape, a parametric resonance had to be introduced, so that we define α as

$$\alpha = \alpha_0(1 + \eta cos\omega_0 t) \tag{3}$$

where η is the amplitude and ω_0 the frequency of the parametric resonance. In the case of a linear oscillator, α_0 would be related to the resonant frequency of the oscillator by $\alpha_0 = (2\pi f_r)^2$. The coefficient α (or α_0 if $\eta = 0$) can be positive or negative. For $\alpha < 0$ we are in the presence of only one potential well, whereas for $\alpha > 0$ there are two of then, the bistable potential. By construction, this model accounts for nonlinearity (parametric resonance and cubic displacement) and for stochasticity (random noise that accounts for local weather conditions). Later on we will see that the model also accounts for non stationarity. As the model is nonlinear, the principle of superposition do not applies, being substituted by the competition between the different frequency components. This is an important point for the interpretation of the main features displayed in Figure 5, consisting in a principal peak at a frequency around 0.21 Hz and a secondary peak at about 0.07 Hz. We will center our study on the principal peak. Because of its character of minimum spectrum, for which the strength of the external forces will also be minimum, Figure 5 can be considered as the BLNS, or reference level. Following an early suggestion by Hasselman (1963) about microseism activity as the (linear) resonant response of a layered medium, we interpret the BLNS as the nonlinear resonant response of a layered structure, instead of being representative of the frequencies of the oceanic waves. This interpretation was already suggested by Correig and Urquizu (2002).

Our interpretation is based on the evolution of the microseism time series in phase space (Correig and Urquizu, 2002) and in the numerical simulations of such evolution, as well as the observed power spectrum, from equation (1). Figure 6 displays the evolution of the computed oscillation in phase space, and in Figure 7 its corresponding power spectrum, representative of the common features of the BLNS of each of the spectrum of the seismic stations used in this study. The numerical values of the model parameters are given in Table 2.

In this numerical simulation the secondary peak of Figure 7 (located at 0.11 Hz), has been included, for the purpose of comparison to observations, as a subharmonic of the frequency associated to α_0 of 0.33 Hz. The more notorious characteristic is that the shape of the main peak is dominated by the strength and frequency of the parametric resonance, that can be further modified if one of the two external forces is close to the frequency associated to α_0 (linear resonance). Note that the morphology of the main peak has the same structure as that observed in Figure 5: a lower wide part and a narrow upper one, separated by a significant change in slope. Because of the strong effect of the resonances (in the numerical model) on the shape of the main peak, we interpret its presence in the observations as a resonant effect, a competition between the proper frequency of the stack of layers (possibly extending to the whole mantle) and the effect of the parametric resonance and external forces, such as weather conditions, meteorology, general atmospheric circulation and oceanic currents, all time dependent. As superposition does not apply, it is not possible to retrieve from data the individual contributions, but only to estimate them through numerical simulations. A further reason in favor of the interpretation in terms of resonance is the lack of stationarity of the time series: numerical simulations with a Duffing oscillator show that stationarity vanishes when resonance is approached. From a more general point of view, this fact was already advanced by Brillouin (1960).

4 Discussion and Conclusions

In order to minimize the influence of the weather conditions on the microseism power spectra, the minimum values of noise for each spectral component has been selected from all available data recorded at five different broad-band seismic stations. The resulting minimum power spectrum has been named Base Level Noise Spectrum

(BLNS) and can be understood as the resonant response of the Earth at the place of the seismic station, because the influence of the external forces (oceanic, climatic and weather activities) will also be minimal. We have found that for the frequency interval of microseism activity, from 0.03 Hz to 1.0 Hz, the BLNS is the same for the five stations, with small amplitude fluctuations, and are characterized by a main spectral peak located at 0.21 Hz and a secondary peak located at 0.07 Hz. These central frequencies are the same for the five analyzed stations, and are in the proportion 1:3 instead of the proportion 1:2 usually accepted and accounted for by the classical Longet-Higgins (1950) and subsequent models (see Webb, 1998, for a review). An inflexion point (a well defined change in the slope) appears at 0.13 Hz, although we do not know at the present time whether it can be considered as a third spectral peak or not. Although more data is needed, the results suggest that the shape of the BLNS could be a universal feature. It seems, therefore, that this general property is independent of the external oceanic-atmospheric forces, and as a consequence, the spectral shape of the BLNS should represent the medium response rather than the source contribution.

As shown by Correig and Urquizú (2002), the shape of the spectral peaks and the motion in phase space can only be modeled by means of a nonlinear, damped, forced oscillator, also able to account for the nonlinearity, stochasticity and non stationarity of the microseism time series. This phenomenological model, with no physical interpretation at the present time, is useful for numerical simulations, as for example for the study of the contributions of the different terms of the oscillator. In this way, we have discovered (not detected in Correig and Urquizú, 2002) the enormous importance of the parametric resonance in modeling the shape and the location of the main peak, without the need to appeal to a classical resonance (external harmonic force close to the proper frequency of the oscillator). By similarity with the oscillators response in the absence of external forces, or an oscillator driven only by noise, we have assimilated the BLNS to the resonant response of a layered medium, may be the whole Earth's mantle.

The above interpretation agrees with the results of Nawa *et al.* (1998), subsequently confirmed by other authors, who were able to detect the free oscillations of the Earth in the absence of earthquakes, and attributing the source of energy to the general atmospheric circulation and ocean dynamics. In the later situation, we are in front of the response of the whole Earth, and the location of the spectral peaks agree with those predicted by the linear theory of free oscillations. However, in the present study, devoted to the frequency interval of microseism activity, there is the need of a nonlinear model to interpret the spectral characteristics, and the source of energy would be that remaining after the main transient atmospheric and oceanic contributions are suppressed, *i.e.*, contributions at all temporal and spatial scales or, in other words, fluctuations at all scales. This situation is formally similar to the blackbody radiation in a cavity (Feynman, 1963): for a given temperature, each mode (frequency of light) has a given energy; once the thermal equilibrium is reached, the spectrum of radiation has the shape given by Plank's law. One interesting feature is that the shape of the spectrum is independent of the geometry of the cavity. In the microseism spectrum, the equivalent of the temperature would be the stress, and the shape of the spectrum at the 'stress equilibrium' could be approximated by the BLNS. It is not known at the present whether the BLNS is independent or not of the geometry of the layered structure. One important difference, however, exist: whereas the blackbody radiation is well predicted by a linear (quantum) system, microseism is nonlinear.

As a general conclusion we can say that the Base Level Noise Spectrum, defined as the minimum values of the microseism time series for each spectral component, has been found for five seismic stations located in different geological units. For the microseism frequency range, the BLNS display an astonishing similarity, suggesting that this can be a universal feature. Finally, the BLNS can be interpreted as the resonant response of a layered structure, and the fluctuations around the BLNS can be interpreted as due to the action of the external forces, *i.e.*, to the oceanic and atmospheric activity.

Acknowledgements

We would like to express gratitude to the Swiss Federal Institute of Technology Zürich, for the facilities providing data from ABSA, EBR and HVAR stations, and for the support equipping POBL. In particular, we wish to thank Suzan van der Lee, Federica Marone an Mark van der Meijde their effort in the selection of data obtained through the MIDSEA project. It is a pleasure to thank Mr. Joan Deu and Mr. Joan Almirall (General and vice-General Director of Túnel del Cadí [TABASA]) who put at our disposal the facilities and logistics for the arrangements and maintenance of CADI station. Mr. Diego García is thanked for his assistance in situ. Father F. Tulla and the community of the Monastery of Poblet are thanked for the facilities in the installation of POBL seismic station. POBL station is supported in part by the Central Nuclear Vandellòs II. This research has been supported in part by the Dirección General de Investigación Científica y Técnica, under Grants PB96-0139-C04-02 and by the Secretaria de Estado de Educación, Universidades, Investigación y Desarrollo, under Grants REN2000-1740-C05-02. Contribution n.XX of the Departament d'Astronomia i Meteorologia of the Universitat de Barcelona.

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Vila, J. and R. Macià, The Broadband Seismic Station CADI (Túnel del Cadí, Eastern Pyrenees), Part II: Long Period Variations, *Bull. Seism. Soc. Am., 92-8*, 3329-3334, 2002.

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Captions

Figure 1: Location map of the seismic stations used in this study.

Figure 2: Base Level Noise Spectrum for the three components CADI seismic station.

Figure 3: Annual Base Level Noise Spectrum (vertical component)of CADI seismic station.

Figure 4: BLNS for the other four stations used in this study. Top figures display the global BLNS for the three components. Bottom figures display the annual BLNS for the vertical component. Asterisks (*) on the legends indicate that the data used do not cover the full year.

Figure 5: Comparison of the BLNS (vertical component) for the five seismic stations analyzed in this study.

Figure 6: Evolution of the computed oscillation in phase space.

Figure 7: Power spectrum, of the computed oscillations shown in Figure 5.

Name	lat.(deg.)	lon.(deg)	alt.(m)	Institution	Time interval
ABSA	36.2765	7.4734	1025	ETH	05/09/2000 - 02/04/2002
CADI	42.3402	1.8412	1207	IEC	07/03/1995 - 09/10/2001
EBRE	40.8228	0.4940	36	ETH	15/06/1999 - 04/11/2000
HVAR	43.1776	16.4490	250	ETH	13/10/1999 - 08/02/2001
POBL	41.3792	1.0834	508	IEC/ETH	14/11/2000 - 26/03/2003

Table 1: List and time of operation of the seismic stations used in this study (see Figure 1)

damping coefficient, δ	0.1
coefficient α_0	-4.0 $^{(1)}$
coefficient of nonlinearity, β	0.1
frequency external force F_1, f_1	0.001
amplitude external force F_1, γ_1	5.0
frequency external force F_2, f_2	0.106
amplitude external force F_2, γ_1	4.0
noise amplitude, ε	2.5
frequency parametric resonance, f_0	0.0005
amplitude parametric resonance, η	0.00003

Table 2: Numerical values of the model parameters. In the linear case, the value $^{(1)}$ would correspond to a resonant frequency of 0.328 Hz.

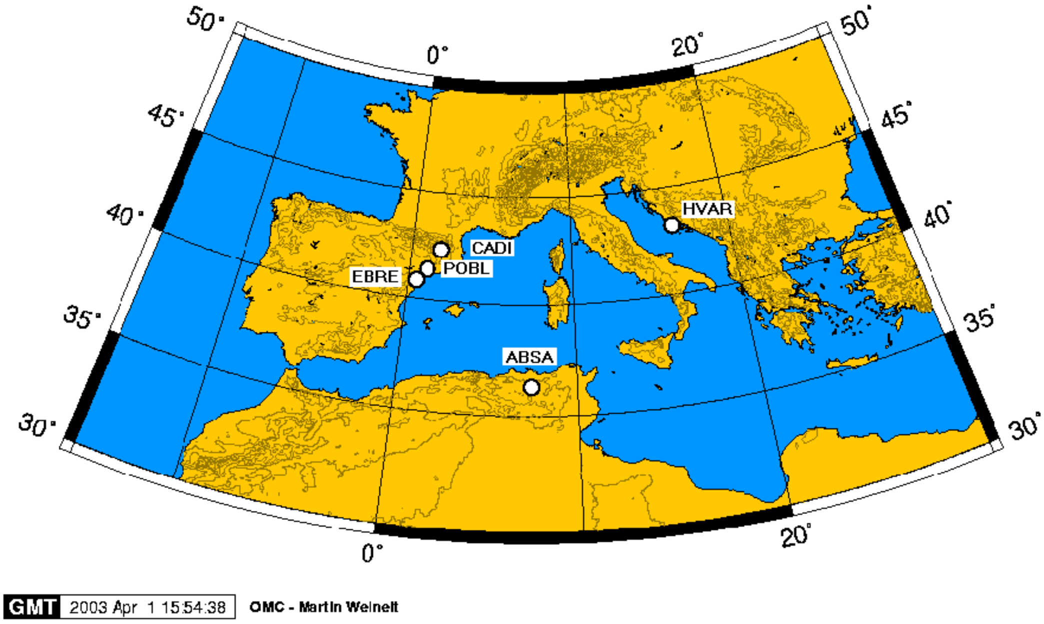
50°
0°
20°
50°
45°
45°
40°
40°
35°
35°
30°
30°
0°
20°
HVAR
CADI
POBL
EBRE
ABSA
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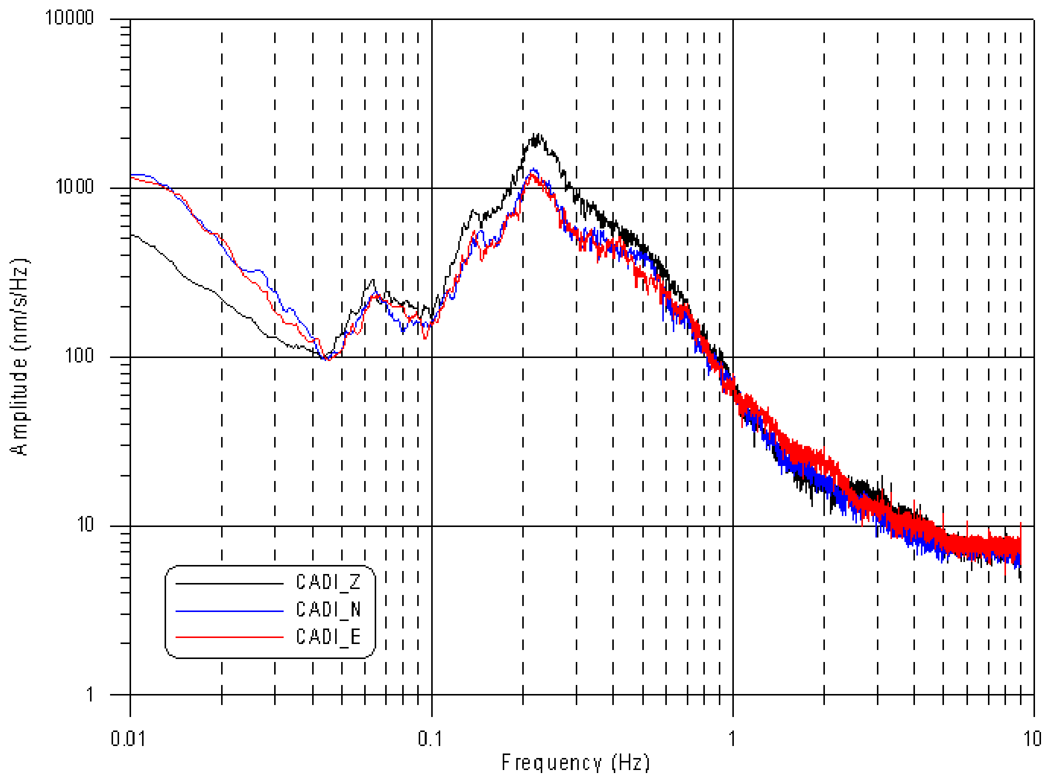
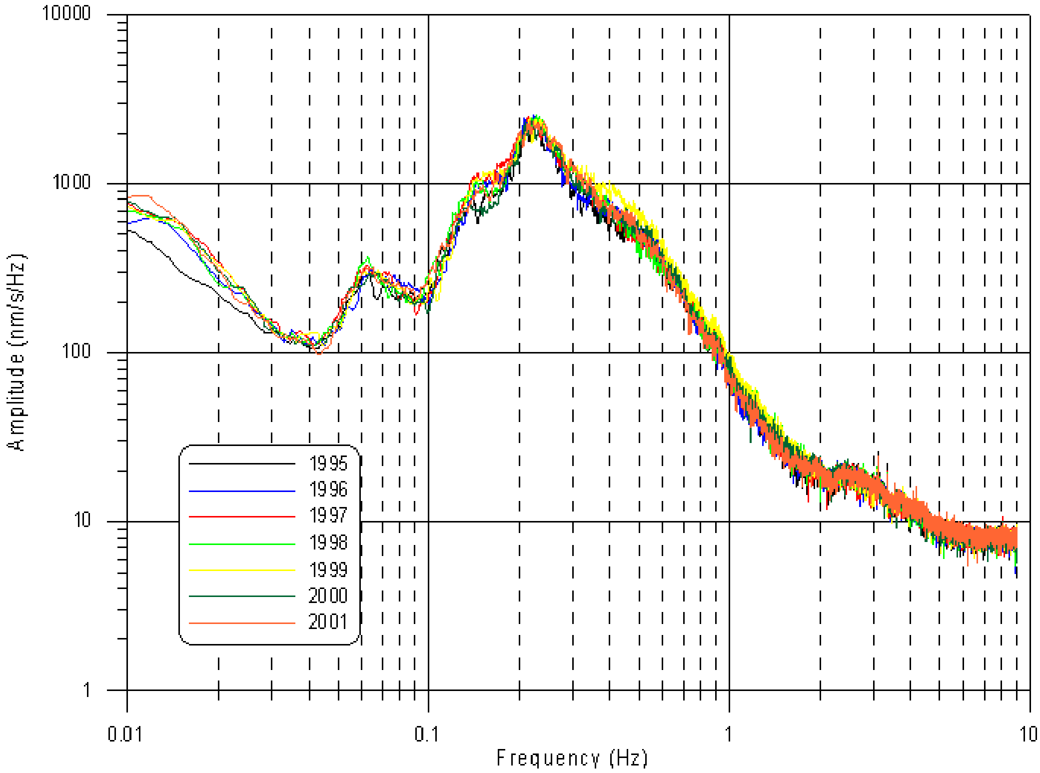
Figure 1



10000
1000
100
10
1
Amplitude (nm/s/Hz)
0.01
0.1
1
10
Frequency (Hz)
CADI_Z
CADI_N
CADI_E

Figure 2



10000
1000
100
10
1
Amplitude (nm/s/Hz)
1995
1996
1997
1998
1999
2000
2001
0.01
0.1
1
10
Frequency (Hz)

Figure 3

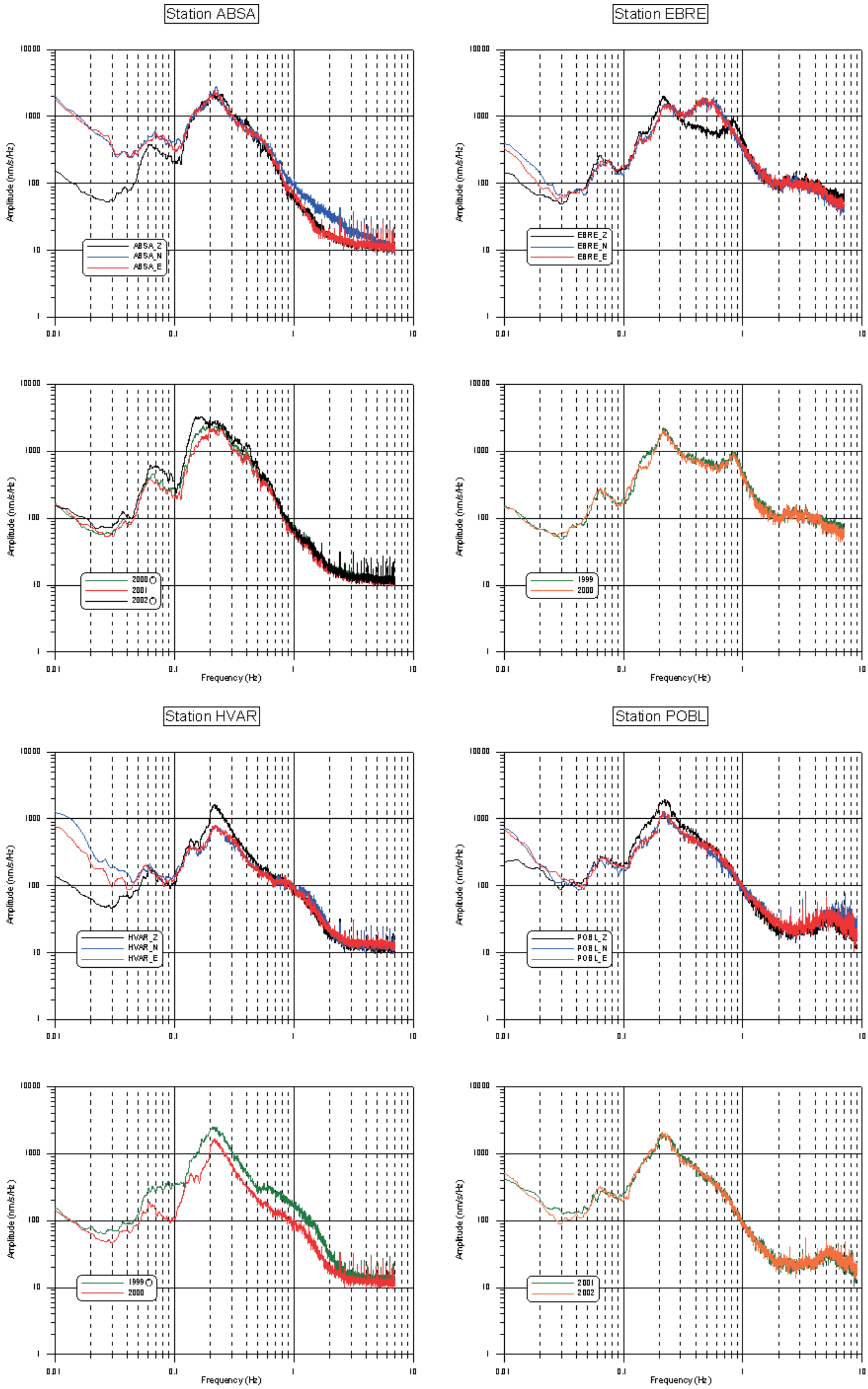

Station ABSA
Station EBRE
Station HVAR
Station POBL
Amplitude (nm/s/Hz)
Frequency (Hz)
10000
1000
100
10
1
0.01
0.1
1
10
ABSA_Z
ABSA_N
ABSA_E
EBRE_Z
EBRE_N
EBRE_E
2000
2001
2002
1999
2000
HVAR_Z
HVAR_N
HVAR_E
POBL_Z
POBL_N
POBL_E
1999
2000
2001
2002

Figure 4

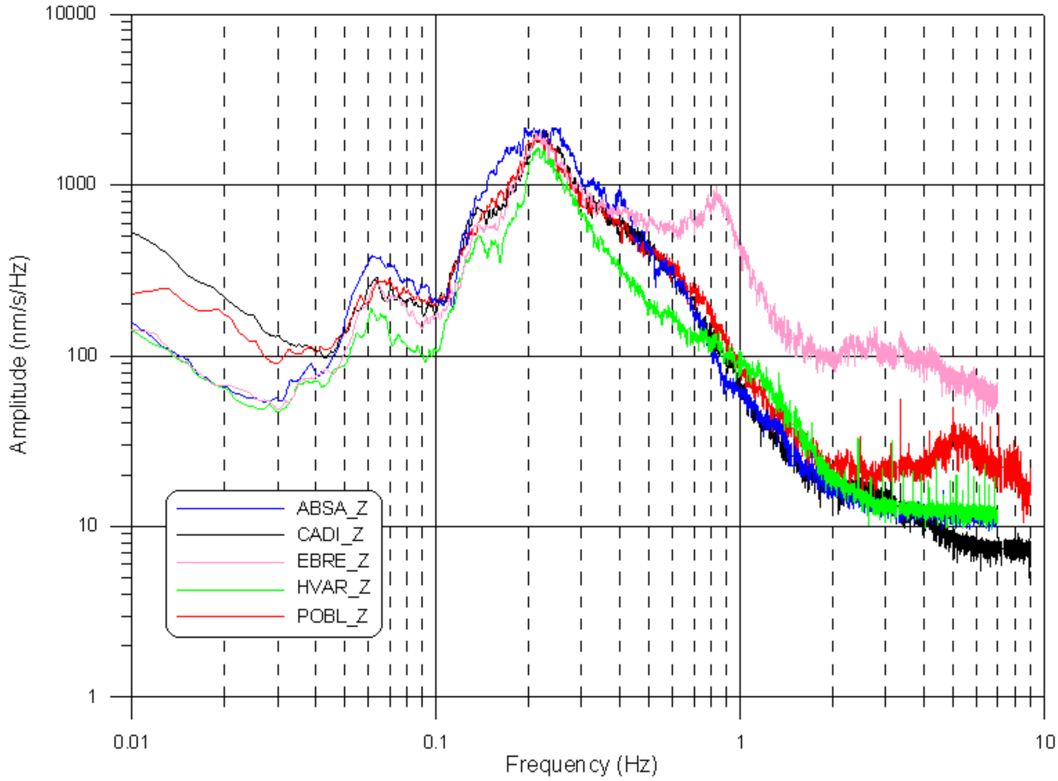

10000
1000
100
10
1
Amplitude (nm/s/Hz)
0.01
0.1
1
10
Frequency (Hz)
ABSA_Z
CADI_Z
EBRE_Z
HVAR_Z
POBL_Z

Figure 5

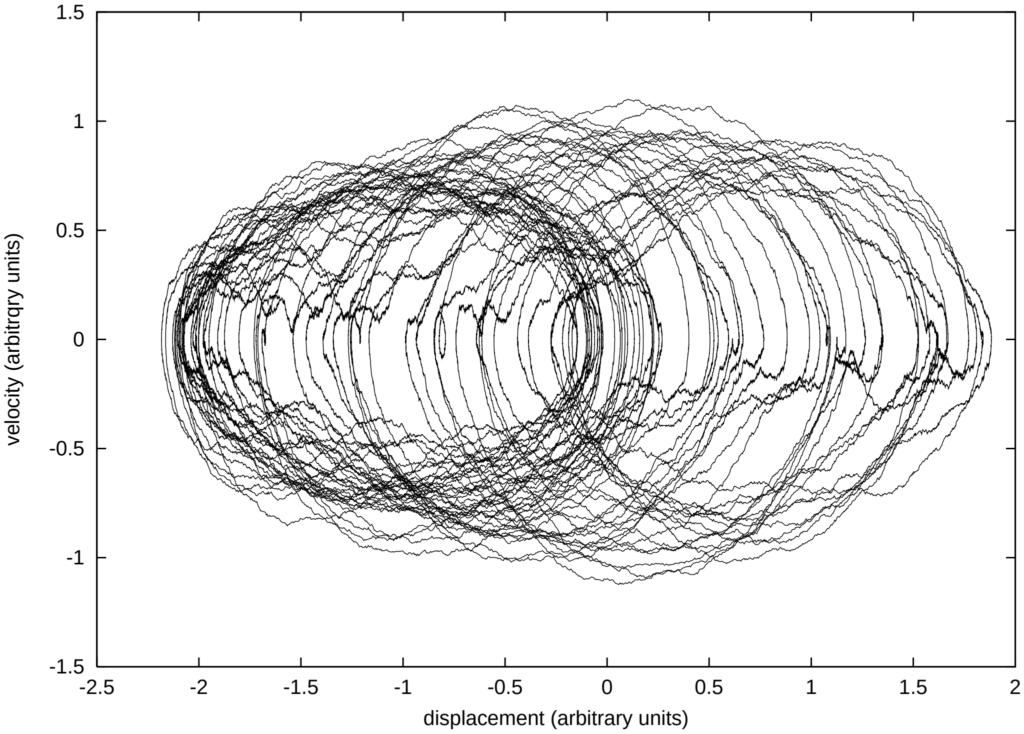

1.5
1
0.5
0
-0.5
-1
-1.5
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
velocity (arbitrqry units)
displacement (arbitrary units)

Figure 6

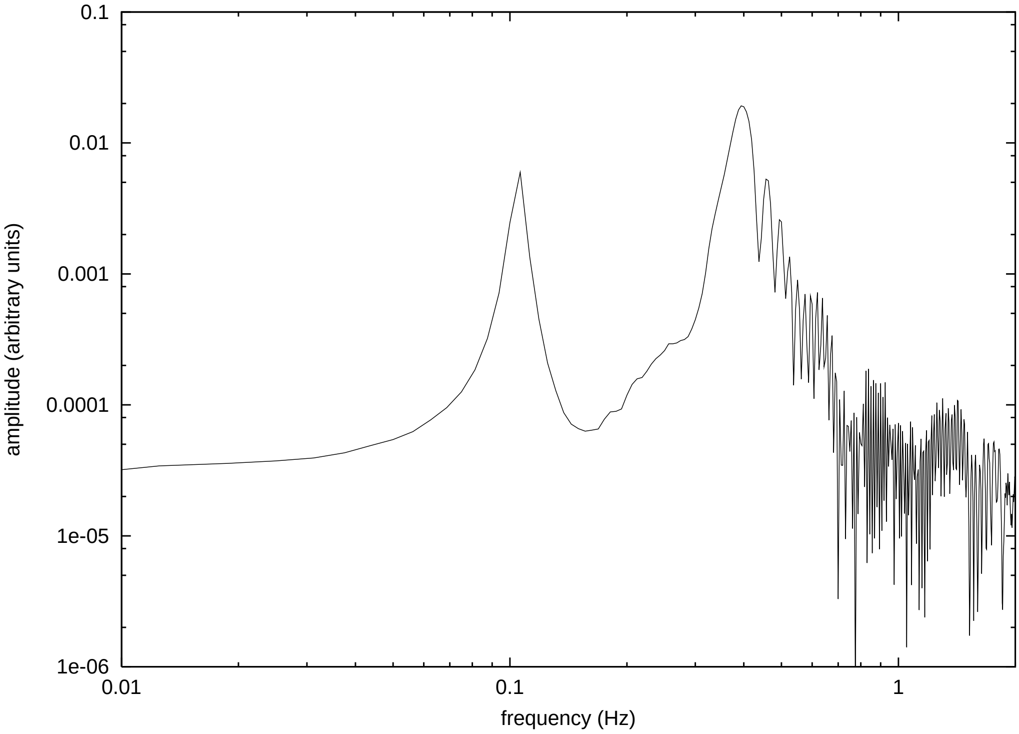

0.1
0.01
0.001
0.0001
1e-05
1e-06
amplitude (arbitrary units)
0.01
0.1
1
frequency (Hz)

Figure 7

A PHENOMENOLOGICAL MODEL FOR VOLCANIC TREMORS

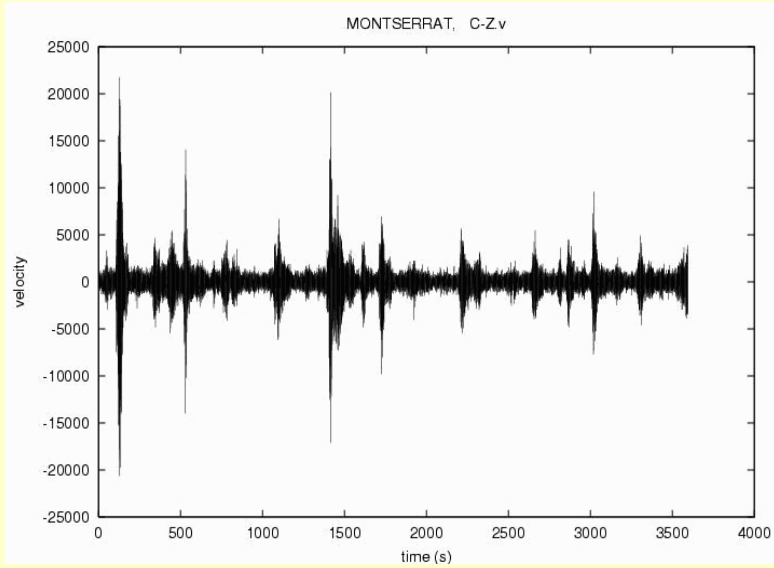
Antoni M. Correig

Universitat de Barcelona

VOLCANIC TREMOR

From the point of view of a recording seismic station, it is commonly accepted that a volcanic tremor is a continuous oscillation with a predominant frequency between 1 – 5 Hz, that may last from a few minutes to several months.

TIME SERIES - 1



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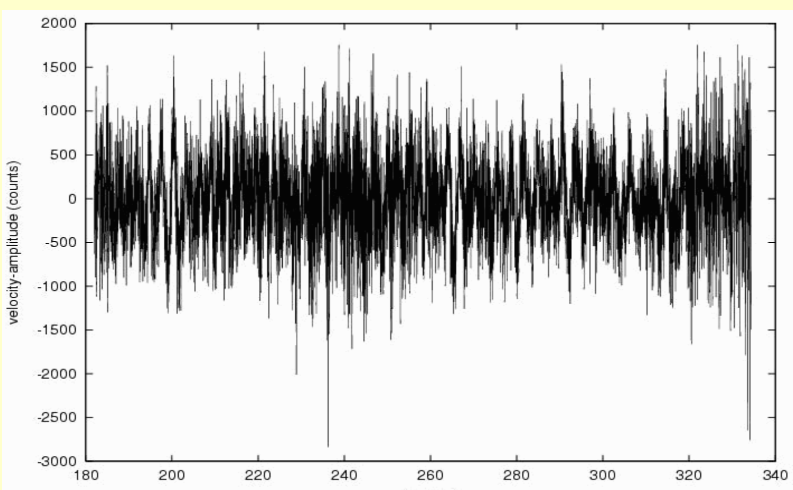
TIME SERIES - 2



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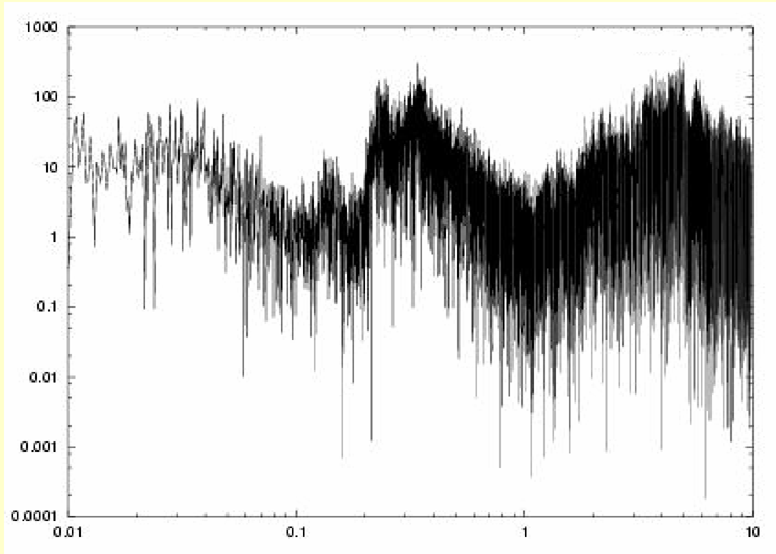
POWER SPECTRUM



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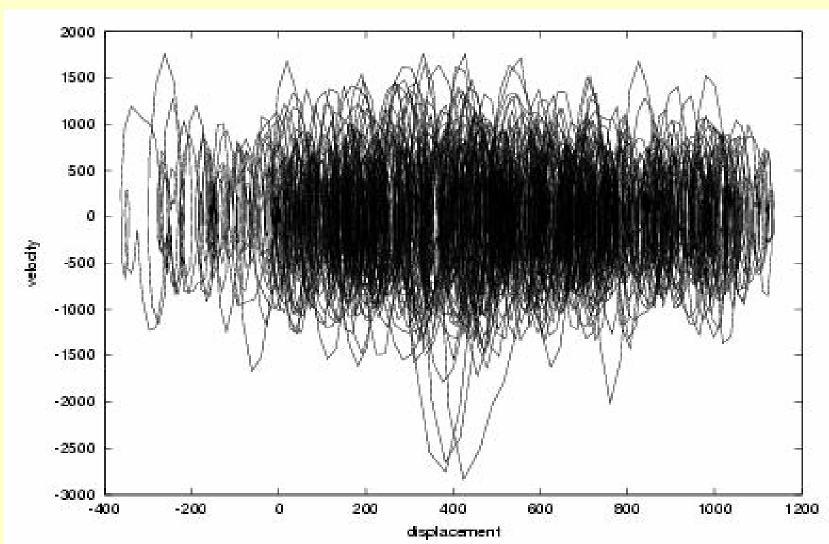
PHASE SPACE - 1



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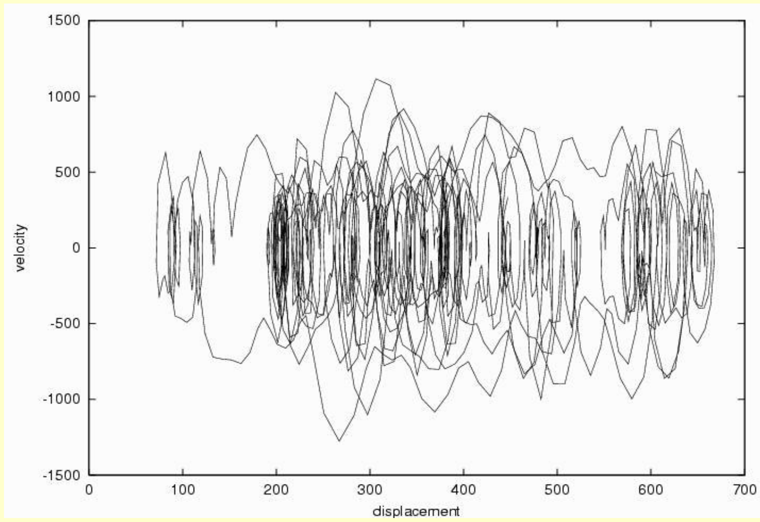
PHASE SPACE - 2



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PHENOMENOLOGICAL MODEL

In a first step we accept the model developed for microseisms.

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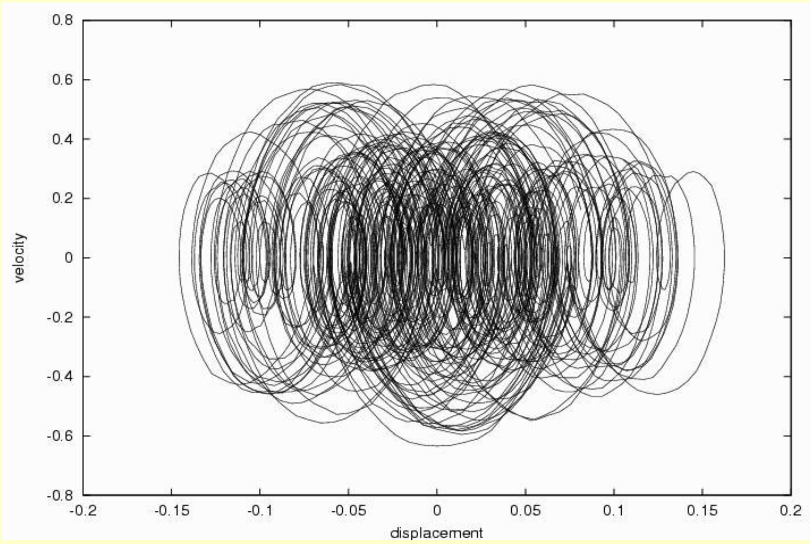
NUMERICAL SIMULATION - 1



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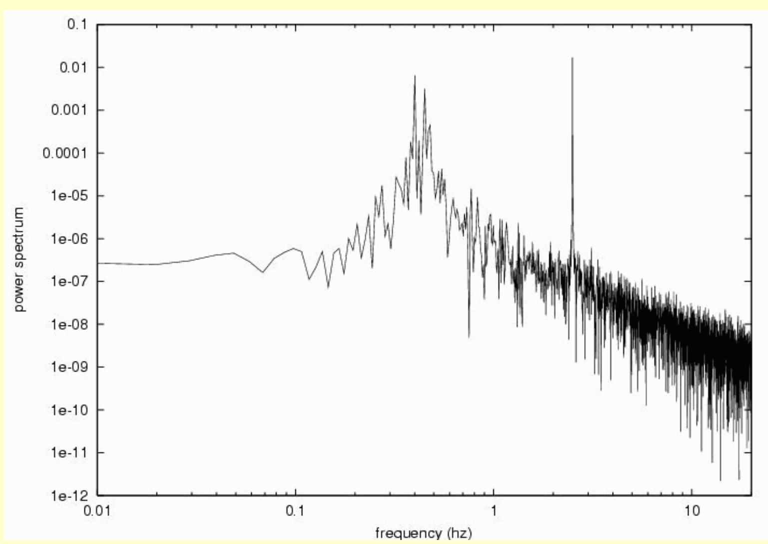
NUMERICAL SIMULATION - 2



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TIME SERIES ANALYSIS

An analysis of both microseisms and volcanic tremors reveals that their corresponding time series are:

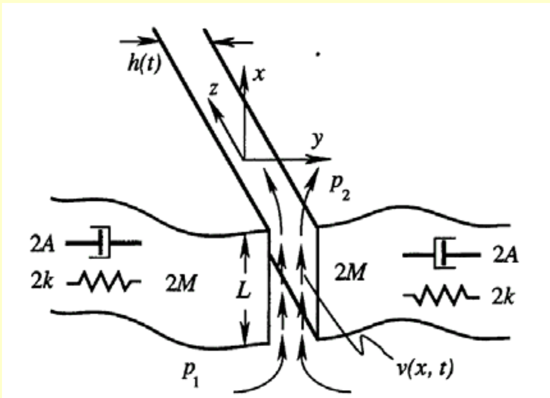
- non-stationary
- non-linear
- stochastic

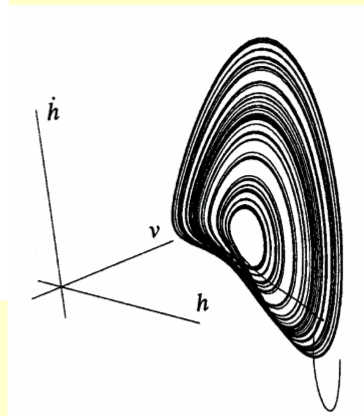
ORIGIN OF THESE FEATURES

Through numerical simulations with the phenomenological model, we have found the following reasons:

- Non-linearity: shown through the numerical simulation
- Stochasticity: due to the noise source component
- Non-stationarity: due to a process of resonance

LUMPED-PARAMETER MODEL OF TREMOR. 1





(Julian, 1994)

LUMPED-PARAMETER MODEL OF TREMOR. 2

$$\rho\dot{v} + \frac{12\eta}{h^2}v = \frac{p_1 - p_2}{L}$$

$$\left[M + \frac{\rho L^3}{12h}\right]\ddot{h} + \left[A + \frac{L^3}{12h}\left(\frac{12\eta}{h^2} - \frac{\rho}{2}\frac{\dot{h}}{h}\right)\right]\dot{h} + k(h - h_0) = L\left[\frac{p_1 + p_2}{2} - \frac{\rho v^2}{2}\right]$$

Rössler Model

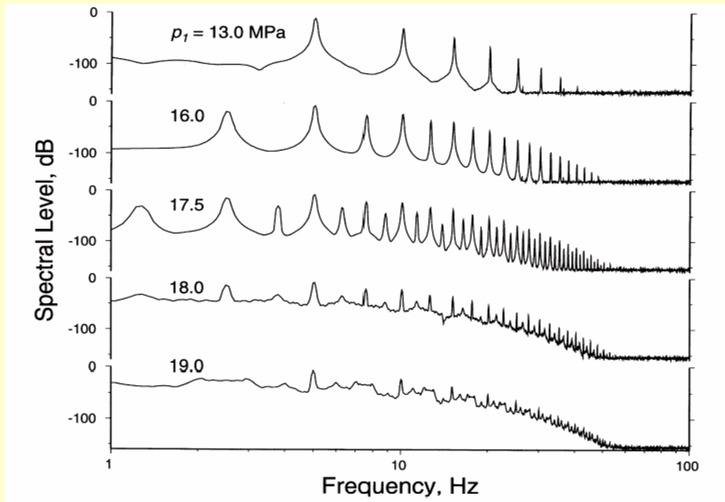
$$\dot{Z} + (c + aY - \dot{Y})Z = b$$

$$\ddot{Y} - a\dot{Y} + Y = -Z$$

Linear oscillator

$$\ddot{x} + 2\gamma\varepsilon_0\dot{x} + \omega_0^2 = F(t)$$

LUMPED-PARAMETER MODEL OF TREMOR. 3



(Julian, 2000)

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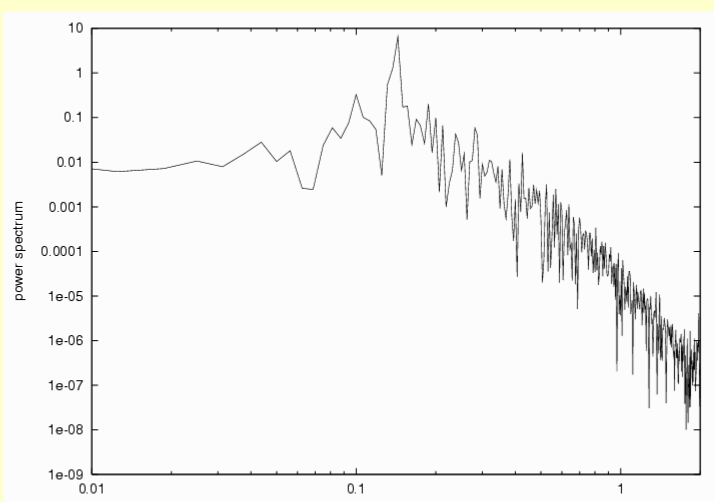
RÖSSLER MODEL



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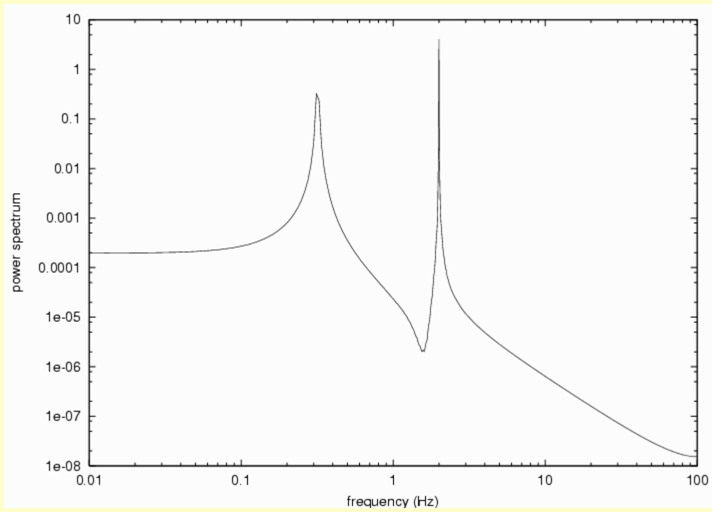
LINEAR OSCILLATOR



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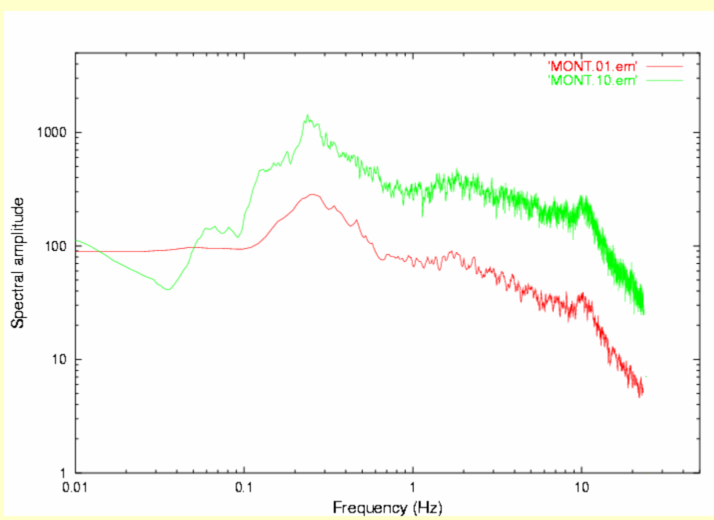
MONTSERRAT MINIMUM SPECTRA



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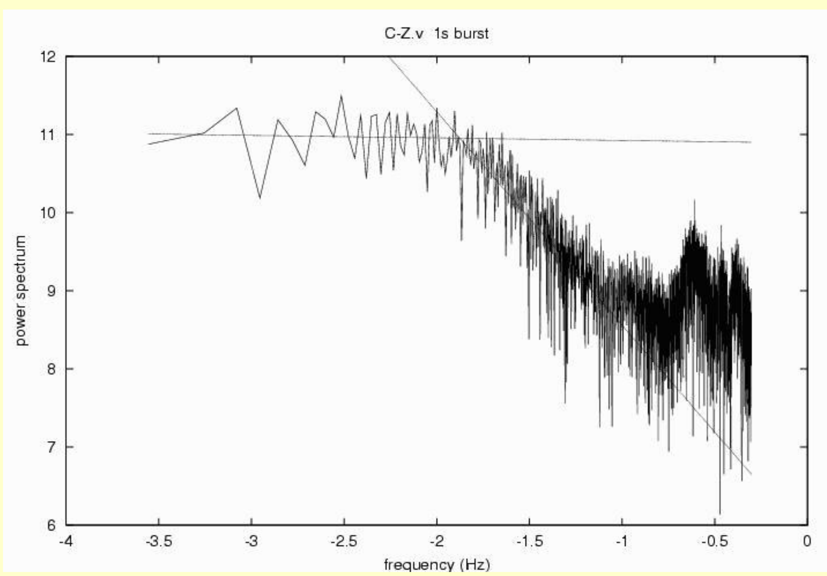
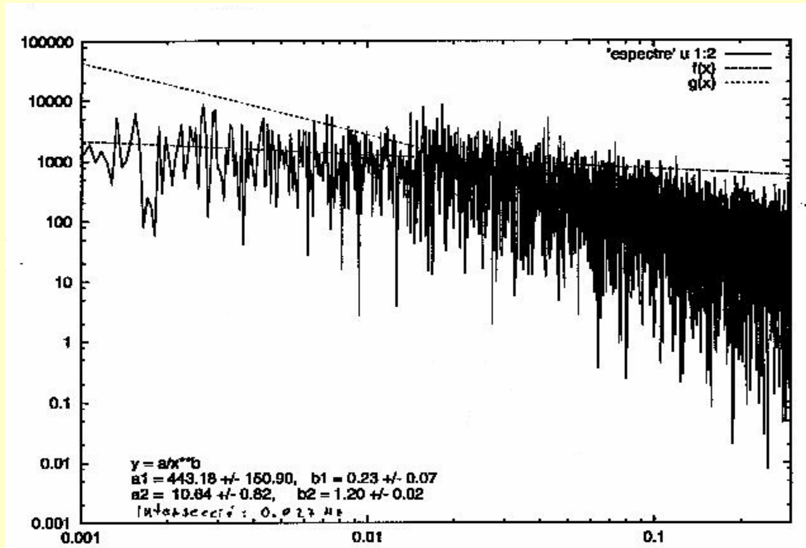
ENERGY TIME SERIES

- Microseisms and volcanic tremors are a continuous flow of energy. The energy can be computed from seismic records (velocity recorders) as the square of the amplitude for a given interval of time (1 s in the present case), giving rise to a new time series.
- The power spectrum of this energy time series (for volcanic tremors as well as for microseisms and numerical simulations) follow the same pattern: two truncated power law **1/f$^{\alpha}$**, followed by a wide spectral peak.
- For low frequencies, up to ~ 0.01 Hz, α ~ 0 (white noise), whereas for the approximate interval 0.01 – 0.2 Hz is α ~ 1.5 for microseisms and volcanic tremors and ~ 3 for the model.

VOLCANIC TREMOR



MICROSEISMS - 1



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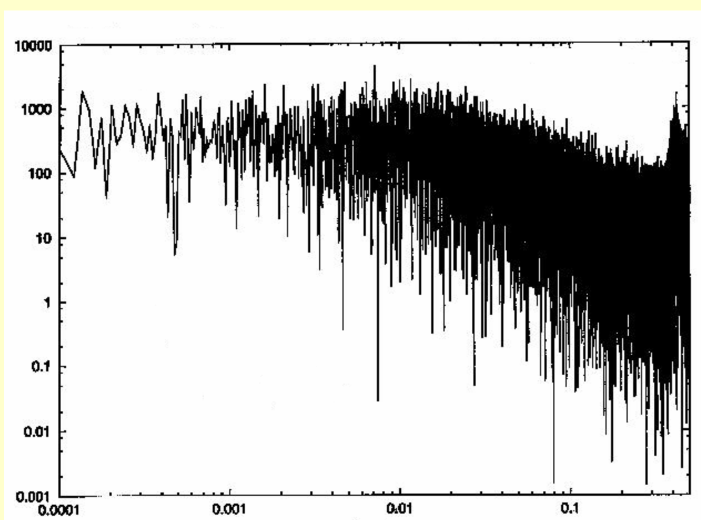
MICROSEISMS - 2



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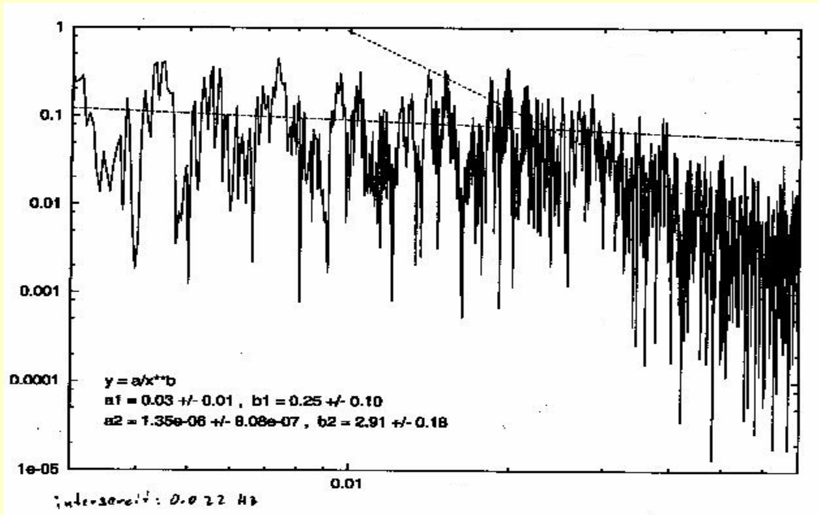
MODEL - 1



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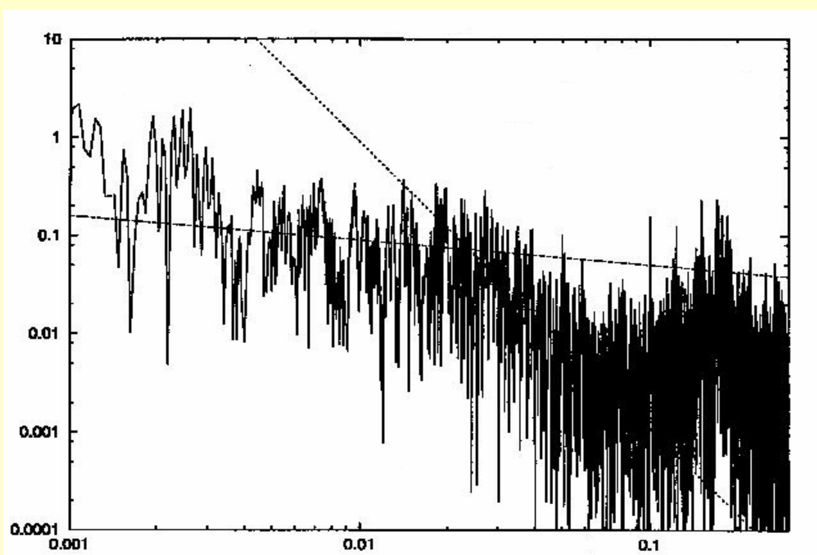
MODEL - 2



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CONJECTURE

A volcanic tremor time series is strongly influenced by the ubiquitous and always present microseisms (medium fluctuations). We propose that volcanic tremors should be modeled in terms of an additive force component in the microseisms' model.

PROPOSED TREMOR'S PHENOMENOLOGICAL MODEL

$$\dot{q} = p$$

$$\dot{p} + \frac{\partial V_0(q)}{\partial q} + \delta p = \sum_{i=1}^{2} \gamma_i cos(\omega_i t) + \varepsilon F(t) + \gamma F_{tr}(t)$$

Where $F_{tr}(t)$ stands for a chaotic source (Julian,1994), and γ is its strength.

POWER SPECTRUM