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Time dependent features in tremor spectra

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Abstract

Harmonic spectral peaks are observed in the tremor spectra of many different volcanoes, and in some cases these spectral lines have been seen to change with time. This has also been observed for the tremor at the Soufrière Hills volcano on Montserrat, West Indies, where the spectral lines are sometimes seen to glide apart before an explosion. We propose a model of repeated triggering of low-frequency earthquakes to explain these gliding lines using the relationship $\delta t = 1/\delta v$, where δt and δv are time and frequency spacing, respectively, and investigate factors which can affect the observation of these spectral peaks. Noise and amplitude variation are shown to have little effect on the spectral peaks; however the time gap between events must be nearly constant over several events. An error with a standard deviation of 2% or less is required for the spectral lines to be observed in the frequency range 0.5–10 Hz. We can reproduce the gliding spectral lines from a specific tremor episode preceding an explosion by changing δt from 1 to 0.31 s over a time period of 12 min. Using this relationship and an Automated Event Classification Analysis Program (AECAP), we can monitor δt over a long time period. The AECAP also extracts other seismic parameters such as energy, duration and spectral characteristics. An initial comparison between low-frequency seismic energy and cyclic tilt shows a correlation between the two, but this does not hold for later cycles.

Keywords: harmonic spectral lines; volcanic tremor; gliding; low-frequency earthquakes; Montserrat; swarms

1. Introduction

Harmonic tremor with peaked spectra has been observed on many different volcanoes around the world. Examples are Mount Semeru, Indonesia (Schlindwein et al., 1995; Julian, 2000), Lascar, Chile (Hellweg, 2000), Arenal, Costa Rica (Hagerty et al., 2000; Julian, 2000), and Montserrat, West Indies (Neuberg et al., 2000). The tremor spectra have peaks at integer harmonic frequencies, which can occasionally be seen to change over time (Benoit and McNutt, 1997; Neuberg et al., 1998), giving the impression of gliding spectral lines.

Latter (1979) was the first to notice that the amplitude spectrum of tremor is very similar to that of low-frequency earthquakes, suggesting that tremor and low-frequency events have a common volcanic source. Fehler (1983) went further by suggesting that harmonic tremor is composed of repeated low-frequency events, which are too close together to be resolved in time.

It has been shown that the spiky spectra can be created by equally spaced seismic events (Gor-

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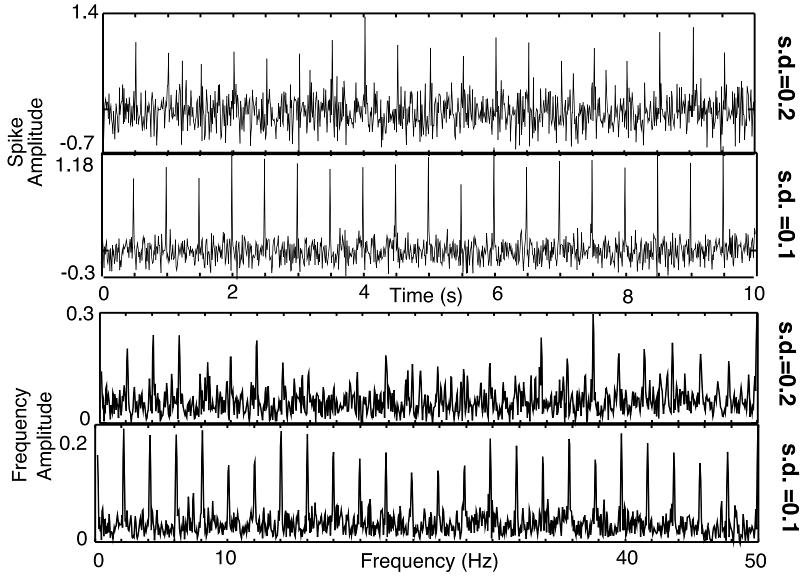

Fig. 1. Two noisy traces with spikes 0.5 s apart, containing noise with a standard deviation of 20% and 10%, respectively. The corresponding amplitude spectra show that for low noise levels of 10%, all of the integer spaced frequency peaks can still be resolved in the frequency range 0.5–10 Hz. This is not the case for the higher noise levels of 20%.

deev, 1993; Schlindwein et al., 1995), with the relationship $\delta t = 1/\delta v$, where δt is the time between events and δv is the frequency gap between spectral peaks. However, Hagerty et al. (2000) point out that the δt between the events must be accurate to a standard deviation of less than 1% to get the signal to noise ratio seen on Arenal.

Changes of the integer harmonics can be used to detect a change in the event triggering frequency and thus tell us more about the behaviour of the source. As such a source is repetitive, a non-destructive feedback system is necessary. Julian (1994) suggests fluid driven oscillations, caused by fluctuations in fluid flow through an elastic walled conduit, as such a feedback system. If damped, this system can produce period doubling, which then leads to chaotic behaviour. Period doubling has been observed on Semeru, Indonesia, and Arenal, Costa Rica (Julian, 2000). However, for Montserrat, this model could not hold because of the extremely high viscosity of the andesite magma.

On Arenal, the spectral lines show small fluctuations during the same tremor episode. On Montserrat, the spectral lines are sometimes seen to follow a systematic pattern by drifting apart prior to an explosive event and converging after the event. This implies that low-frequency events are triggered more frequently before an eruption and less frequently after it. Based on this observation, Neuberg (2000) suggested a link to the pressurisation of the volcanic system by relating triggering frequency to magma pressure and gas volume fraction.

The spacing between single events can be easily determined in the time domain, but when the low-frequency events can no longer be resolved in the time domain, we can use the frequency domain to find the spacing of events, δt, via the spacing of the spectral lines, δv. This will allow further analysis of δt and its role in the pressurisation of the volcanic system.

We begin, in Section 2, by investigating the factors which could affect the occurrence of the integer harmonic spectral peaks.

2. Spiky spectra and factors affecting them

The relationship between the intermittency of consecutive events and the frequencies of harmonic spectral lines is given by $\delta t = 1/\delta v$. A series of repeated low-frequency events is equivalent to a time series of spikes convolved with a low-frequency earthquake. As a convolution in the time domain is a multiplication in the frequency domain, the frequency peaks that occur will be limited to the frequency range of the low-frequency earthquake, which, in the case of Montserrat, is approximately 0.5–10 Hz.

There are four main factors to be considered which could affect the occurrence of the frequency peaks. An investigation of them is necessary to find out to what degree they will affect the spiky spectra of the tremor seen on Montserrat. The methods discussed are applied to synthetic time series.

The first factor to consider is noise. How much noise can there be, before the spectral peaks can no longer be observed? Two traces were created where spikes are separated by 0.5 s. Synthetic noise, with a Gaussian distribution, was added to the traces, with standard deviations of 10% and 20% (Fig. 1). The amplitude spectra, also in Fig. 1, demonstrate that with low noise levels of 10% the spectral peaks can be clearly observed, but at higher noise levels of 20% the relevant spectral data is obscured. On Montserrat, the primary source of non-volcanic noise is ocean microseisms; all other sources of noise are small by comparison. However, this source of noise is not large enough to obscure the Montserrat data with which we are working.

The second factor to be considered is variation of amplitude. When low-frequency earthquakes are seen leading up to an explosion, they occur more frequently and often form cyclic swarms (Fig. 2). These events are very similar in shape and frequency content, but it is apparent that the event amplitude varies widely. How does this amplitude variation affect the frequency spectrum?

If the amplitude of the earthquakes is varied randomly, the amplitude spectrum will be unaffected. However, if the variation itself is periodic, the period of the amplitude modulation can be seen in the amplitude spectrum. This frequency is marked by a much smaller peak and can only be seen when the period of modulation is small enough to be resolved in the amplitude spectrum. For example, the cyclic behaviour of the low-frequency swarms in Fig. 2 shows a period of approximately 5 min. This translates into $\delta v = 0.003$ Hz, which cannot be resolved in the amplitude spectrum. Therefore, for the example shown, amplitude variations of repeated low-frequency

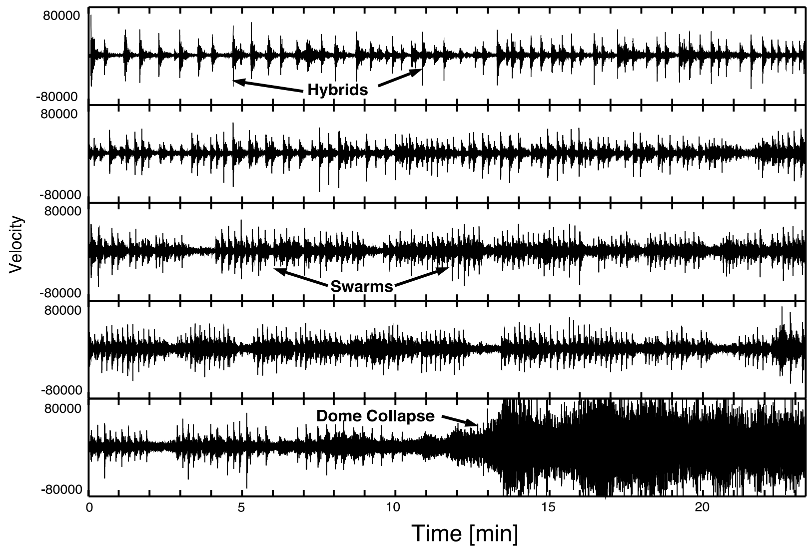

Fig. 2. A sample of repeated low-frequency (hybrid) events in the build up to the 25 June 1997 dome collapse, seismogram starts at 15:11. Examples of earthquake swarms and period halving can be observed in this sequence.

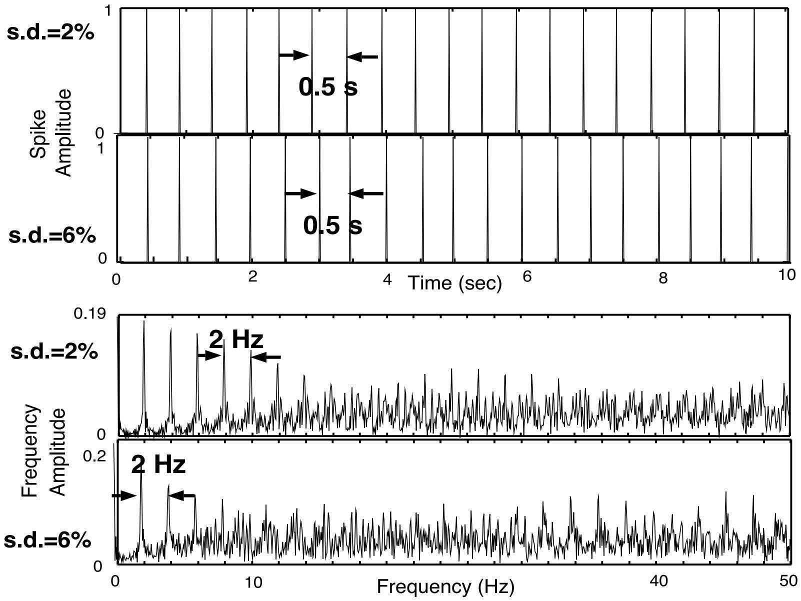

Fig. 3. Examples of the effect of δt varying with a standard deviation of 2% and 6%, respectively. The amplitude spectra show that although the peaks can still be observed for a frequency range up to 14 Hz with a 2% variation, only 2 peaks can be seen with 6% variation.

events do not affect the occurrence of harmonic spectral lines.

The next factor is the stability of δt. How far can δt vary and still create the harmonic spectral lines? Fig. 3 shows two time series with spikes 0.5 s apart, having a standard deviation of 2% and 6%, respectively. The amplitude spectra, also in Fig. 3, show that while a standard deviation of 2% still yields distinct spectral lines up to 14 Hz, 6% produces a random spectra. This means that for the frequency range of 0.5–10 Hz, for low-frequency earthquakes on Montserrat, and a standard deviation of 2%, all of the spectral peaks could still be seen.

Although 2% is larger than the value suggested by Hagerty et al., (2000), it is still very small. For the example trace with $\delta t = 0.5$ s, the standard deviation is only 1/100 s. This means that there must be very little variation in δt to produce the peaked spectra seen on Montserrat, or in turn, the occurrence of spectral lines indicates a very precise and stable triggering mechanism.

The gliding spectral lines on Montserrat are produced by merging of low-frequency events, i.e. they can be explained by a gradual decrease of δt. In the following, we study a spectrum containing a varying δt.

When the spectrum contains two different intermittencies, δt (Fig. 4), the corresponding spectral signature, δv, can be observed in the frequency domain. Where two frequency peaks coincide, they positively interfere to produce larger peaks, producing a periodic amplitude variation in the frequency spectrum. When more than two distinct intermittencies, δt, are present, the spectrum becomes very difficult to interpret. Some peaks interfere constructively, others interfere destructively and others are too close together to be resolved. Therefore, when looking for changes in δt, it is necessary to use a spectrogram with appropriate temporal resolution, rather than to interpret the spectrum of the entire sequence in which δt changes.

3. Period doubling and gliding spectral lines

Before an explosive event on Montserrat, single low-frequency events can often merge into harmonic tremor. When a spectrogram of the tremor

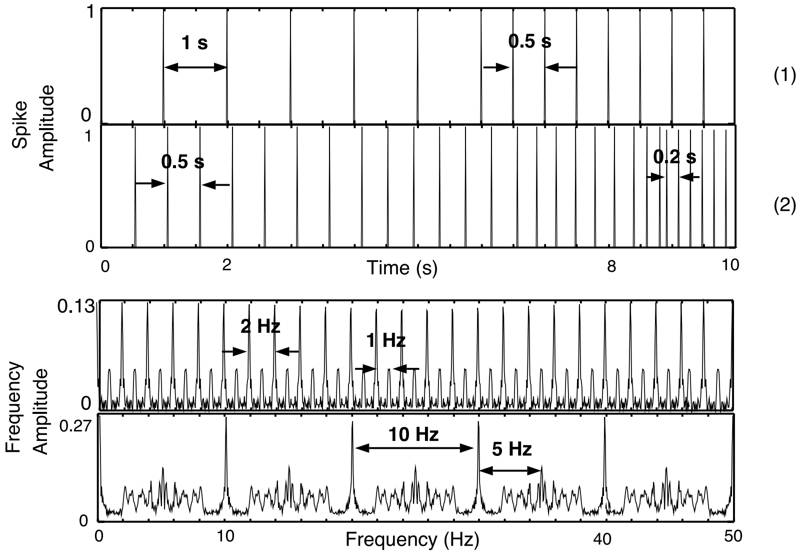

Fig. 4. Changing δt: for trace 1, $\delta t = 1$ s and 0.5 s, for trace 2, $\delta t = 0.5$, 0.4, 0.3 and 0.2 s. In the corresponding amplitude spectra, the dominant frequency spacing is 2 Hz and 10 Hz, respectively, giving $\delta t =$ to 0.5 s and 0.1 s. A spectrogram with the correct temporal resolution should be used when more than one δt is present.

bands is taken, a gliding of the spectral lines can be seen. An example of this, from 7 January 1999, is depicted in Fig. 5. The spectral lines diverge as the explosion is approached and, in this case, they disappear after the explosion. Other examples of this gliding can be seen on 6 and 12 February 1997.

The constant periodicity, δt, mentioned in Section 2, suggests that a feedback system is required whenever harmonic spectral lines are observed.

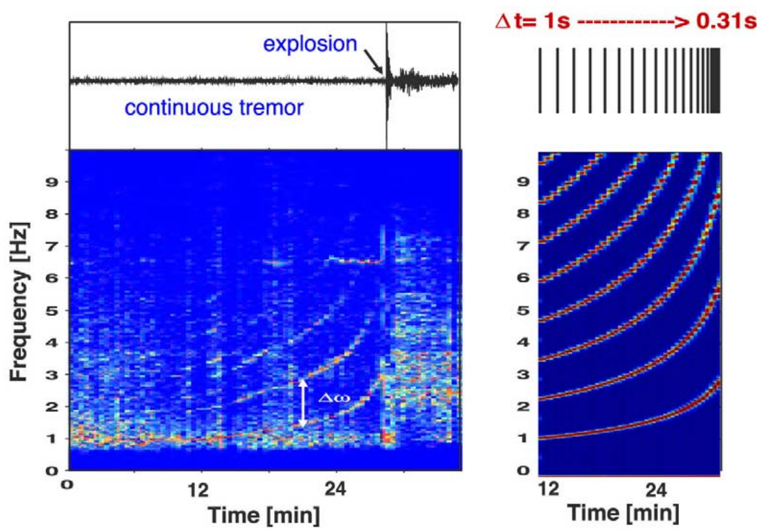

Fig. 5. Comparison between a spectrogram of tremor taken from Montserrat on 7 January 1999 (14:40 UT), and a spectrogram of a synthetic time series. The synthetic series reproduces the tremor spectrogram by reducing δt from 1 to 0.31 s over a period of 12 min.

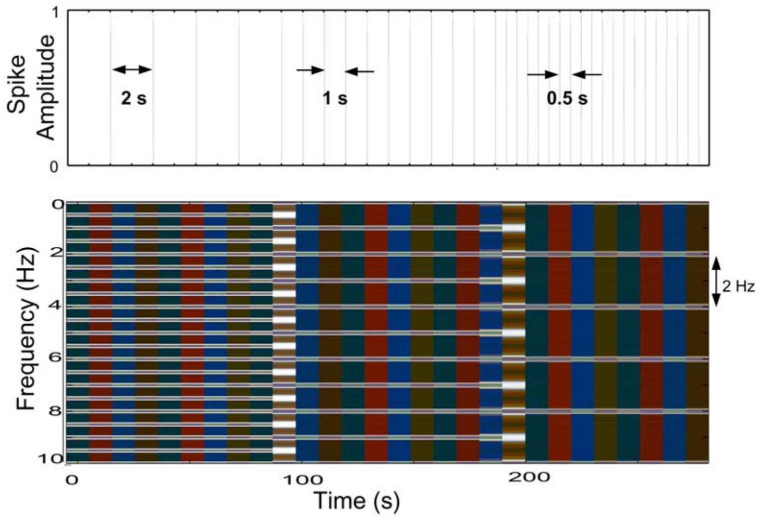

Fig. 6. Period halving in the frequency domain. As δt decreases from 2 to 1 s, and finally to 0.5 s, δv increases from 0.5 to 1 Hz, and finally to 2 Hz.

For a non-linear feedback system, we would expect to see period doubling (Julian, 1994), or period halving, so we should investigate how it would appear in a spectrogram. Fig. 6 shows a synthetic time series of spikes with two period halving events, where intially δt is 2 s, halves to 1 s and halves again to 0.5 s. Beneath the time series is a spectrogram, which shows the corresponding frequency doubling. It has a very distinct pattern which can be easily observed in a spectrogram.

The repeated low-frequency events in Fig. 2 show a decrease in intermittency, δt, and this decrease appears to be period halving. However, examples from Montserrat are by far less apparent that those used by Julian (2000).

However, it is clear from these results that to produce the gliding lines from the example in Fig. 5, δt must decrease gradually over time. To reproduce these gliding spectral lines, δt has been decreased from 1 to 0.31 s over a period of 12 min. Results are shown in Fig. 5, where the gliding lines are reproduced very closely. For the real data from Montserrat, the visible lines are limited by the bandwidth of the low-frequency events which make up the tremor, approximately 0.5–10 Hz, while the synthetic spectrogram is produced by repeated delta functions, which have a white spectrum.

4. Automated event classification analysis

A non-destructive feedback system is necessary to produce the stable δt required to generate the gliding spectral lines. Thus, δt is an important parameter in understanding the behaviour and source of the low-frequency events. During harmonic tremor episodes we can retrieve δt from the frequency domain via δv; however at other times δt is too large and δv cannot be resolved. It can, however, be measured directly in the time domain, to which end we developed an Automated Event Classification Analysis Program (AECAP).

This algorithm finds seismic events and classifies them into three categories, which are low-frequency events, rockfall signals and all other events. In addition it extracts parameters which include δt, energy, amplitude, duration and spectral information. Once the events merge into tremor and are no longer distinct, the programme identifies this time window as tremor. However, we can now retrieve δt from the frequency domain, from the spectral lines, by using the

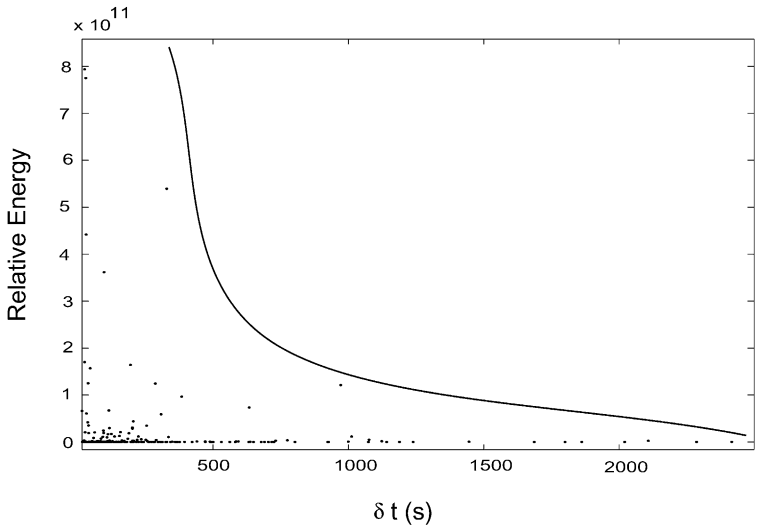

Fig. 7. δt vs. relative energy, where relative energy is the sum of the squared amplitudes of the event. All the low-frequency events from 27 June 1997 (dots) are plotted. There is an inverse relationship between the two, an approximation is shown by the dark line. As t becomes small, energy increases, implying a build up in pressure within the volcano.

$\delta t = 1/\delta v$ relationship, which so far has been done manually. This is only possible when δt varies with a standard deviation of less than 2%.

We can monitor δt over long time periods, and also zoom in on areas relating to specific volcanic behaviour, such as periods of high and low activity. We intend to analyse these data sets statistically and compare them to other seismic parameters retrieved by the AECAP, as well as to the tilt/pressurisation of the volcano.

An initial comparison for 27 June 1997 is shown in Fig. 7. δt is plotted vs. relative energy of the low-frequency events, where the relative energy is the sum of the squared amplitudes of the low-frequency event. If δt is small, the energy of the event is large, and vice versa, implying an increase in the energy and pressure as the low-frequency events start to merge.

Previous work by Voight et al. (1998) has linked the low-frequency earthquakes to the pressurisation of the volcano, by using comparisons between tilt cycles and real-time seismic amplitude measurement (RSAM) data. RSAM is a 1-min average of the seismic amplitude (Endo and Murray, 1991), which contains information about all seismic energy, including rockfall, volcano–tectonic events, local earthquakes and non-volcanic noise sources such as weather, ocean microseisms and traffic.

In Fig. 8 the tilt cycles are compared with seismic parameters from the low-frequency events only. There are 3.5 days of data, from 21 June 1997, 19:11 UT. The low-frequency energy is cyclic (Fig. 8a) and agrees with the tilt cycles, but the seismic energy increases some time after the tilt inflation and decreases with the tilt deflation. This supports a relationship between pressurisation and low-frequency earthquakes. However, a more recent comparison of the tilt and RSAM cycles, for the period June–September 1997, shows a wide variation of phase differences between the two parameters for this time period (Thompson et al., 2001). This is supported by an initial comparison of tilt cycles two days after Fig. 8 with low-frequency energy, which shows that the correlation deteriorates over the period under consideration.

As expected from Fig. 7, δt is inversely correlated with the tilt cycles (Fig. 8b), showing that at this point, the low-frequency events begin to merge at the peak of the cycle, i.e. during an inflation of the volcanic edifice.

The percentage of spectral energy below 2 Hz also corresponds to the tilt cycles (Fig. 8c), imply-

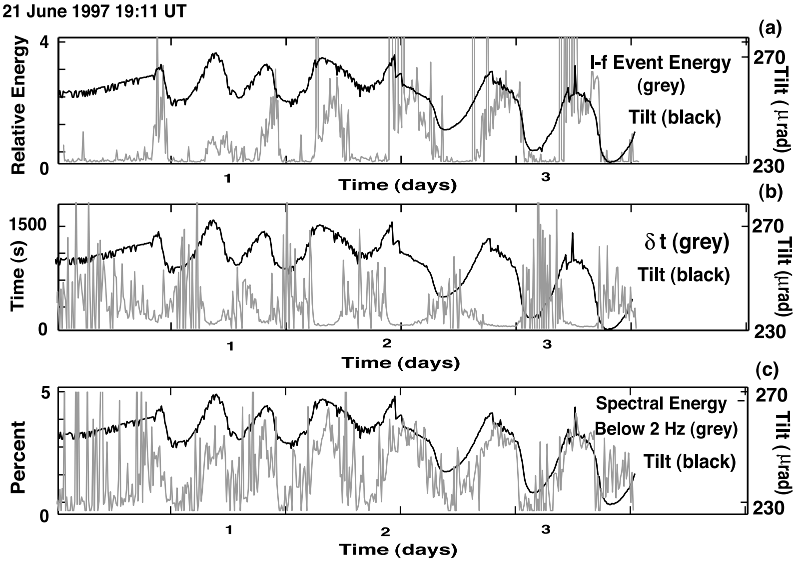

Fig. 8. Comparison of tilt cycles with seismic parameters for 3.5 days, from 21 June 1997, 19:11 UT. The tilt range is approximately 40 microradians. Both the low-frequency event energy (a) and the percentage of spectral energy below 2 Hz (c) are cyclic and appear to match the tilt cycles. This implies a relationship between the pressurisation, the energy and the spectral behaviour. However, there is a time delay between the tilt inflation and the increase in seismic energy. For δt (b), the pattern is inverse, as the low-frequency events become very close together at the peak of the tilt cycles.

ing a change in spectral behaviour during the pressurisation cycle. This may be linked to the conduit resonance model presented by Neuberg (2000), or to changes in source depth, which would affect the attenuation of the high-frequency seismic energy.

5. Conclusions

To produce the spectral peaks at integer harmonics, a stable triggering mechanism is necessary. The spacing between the events must have a variation of less than 2%. This implies a non-destructive feedback system as a source of the low-frequency events.

In the case where this precise triggering produces the spectral peaks, we can retrieve δt from the frequency domain using the relationship $\delta t = 1/\delta v$, where δt and δv are the time and frequency spacing, respectively.

Using this relationship, we can reproduce the gliding spectral lines in the Montserrat data, by gradually decreasing δt over the relevant time period.

It becomes apparent that δt is an important parameter in understanding the behaviour and source of the low-frequency events. Events become close together during the harmonic tremor episodes, and also at the peak inflation of cyclic tilt, linking the low-frequency events to the pressurisation of the volcanic system.

To find δt outside these tremor episodes, the AECAP was developed. It finds, classifies and analyses the seismic events and extracts parameters which include δt, duration, amplitude, energy and spectral information.

An initial comparison between low-frequency seismic energy and cyclic tilt shows a close relationship between the two. The energy increases near the peak of the tilt inflation and decreases in line with the tilt deflation. However, this relationship is not maintained for the tilt cycles a few days later.

We will continue by using the AECAP to analyse a large seismic data set, of at least a year in length. The parameters extracted will then be compared to each other, to the available tilt data and to the visual observations of volcanic activity. There will also be the possibility of the

AECAP being used as a monitoring tool for the Soufrière Hills volcano.

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