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Characterization of harmonic tremor at Santiaguito volcano and its implications for eruption mechanisms

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CHARACTERIZATION OF HARMONIC TREMOR AT SANTIAGUITO
VOLCANO AND ITS IMPLICATIONS FOR ERUPTION MECHANISMS

By:

Kyle Arthur Brill

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

(Geology)

MICHIGAN TECHNOLOGICAL UNIVERSITY

2011

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This thesis, "Characterization of Harmonic Tremor at Santiaguito Volcano and its Implications for Eruption Mechanisms," is hereby approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE IN GEOLOGY.

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Dedication

Para los habitantes de El Palmar, Quetzaltenango, Guatemala.

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Abstract

We observed Santiaguito volcano in southwestern Guatemala from March 2008 - March 2010. Seismic and infrasound data collected between January and March of 2009 contain records of many diverse processes occurring at the dacitic dome complex, including the recurrence of short lived (30-200 seconds in duration) harmonic tremor concurrent with ash poor gas emissions from the volcano. We employ several different analytical techniques to examine different portions of the tremor and source mechanisms. We use the parameters derived by this analysis to compare the feasibility of several suggested models of eruption mechanisms, and determine that this type of harmonic tremor is most justifiably generated by the flow of gas through crack networks generated by shear fracture along the magma conduit margin.

1 Introduction

Eruption forecasting is a major goal of the study of volcanic processes, and there are many techniques employed to aid the understanding of new activity when volcanoes begin to grumble and groan after long periods of sleep. Interpretation of these signals at newly active volcanoes is rooted in observations from other systems. Monitoring active volcanoes is therefore useful not only to the population living in the shadows of these smoking mountains, but also to all other groups living near yet slumbering giants.

Any serious volcano monitoring effort necessarily involves the elucidation of seismic signals. Volcanoes present challenges to this task not found in other environments; the interaction of many materials in different phases due to varying pressures and temperatures produce rich signals from a variety of sources. These sources may change over time, but the propagation medium may also change over time, which complicates the discrimination of source and path affects. One type of signal that can vary over time is volcanic tremor, a persistent ground motion that occurs on a time scale from minutes to days and is associated with different types of material transport beneath a volcano (Konstantinou and Schlindwein 2003).

Volcanic tremor is difficult to interpret because it often manifests smoothly out of background signal. Without a distinct and easily recognizable beginning, identifying wave types and arrival times at different locations becomes nearly impossible (Hofstetter and Malone 1986). Tremor is often therefore classified in terms of frequency content and time duration of the signal. Konstantinou and Schlindwein (2003) summarize five different modifying terms used to describe different behaviors. In the time domain they describe banded tremor as bursts of tremor separated from each other in time, so that they appear as bands or stripes on a seismogram; spasmodic tremor as continuous but with varying amplitudes; and tremor storm as many small tremor bursts contemporaneous with background earthquake activity. In the frequency domain, monochromatic (also called monotonic) tremor consists of only one sharp peak in a narrow frequency band, whereas harmonic tremor consists of multiple spectral peaks with a fundamental frequency and harmonic overtones at integer multiples. Most tremor is concentrated between 0.5 and 7 Hz, but these overtones may achieve frequencies over 10 Hz.

We observed several types of tremor at Santiaguito volcano in south-western Guatemala from January to April 2009 with both broadband seismic and infrasound sensors. Of particular interest are episodes of harmonic tremor sometimes preceding and often following explosion signals. Tremor signals displayed both emergent and impulsive onsets, pronounced spectral peaks in tight frequency bands and gradual shifts in tremor frequencies over time. In the 131 instances of this harmonic tremor behavior, the spacing of the spectral peaks varies from one event to another and the peaks often change in

frequency over the course of selfsame events. Fifty-two of these events also show the same peaking in the infrasound data.

There are many examples of similar tremor in the literature: Hellweg (1999a) at Lascar volcano in Chile, Schlinwein and others at Mt. Semeru in Indonesia (1995) , Hagarty and others (2000) at Arenal in Costa Rica, Johnson and Lees (2000) at Karymsky in Russia and Sangay in Ecuador, and Lees and others (2008) at Reventador in Ecuador all document similar frequency banding and have generally characterized the activity as harmonic tremor (Julian 2000). Authors have varying explanations for the source of these signals, and each explanation has different implications for the eruption mechanisms at their respective volcanoes. As eruption mechanisms at Santiaguito have been discussed extensively in the literature (Bluth and Rose 2004; Johnson et al. 2008; Sahetapy-Engel et al. 2008; Johnson et al. 2009; Sahetapy-Engel and Harris 2009; Holland et al. 2011), this work examines the nuances of these harmonic tremor events and seeks to apply information extracted from them to comment on models of eruption mechanisms currently proposed for Santiaguito.

2 Background

2.1 Geologic Setting and Eruption History

Rose and others (2002) described Santiaguito volcano in south-western Guatemala as a volcanological laboratory because of ongoing activity, relative ease of access, and the unique observational point provided by the edifice of the parent volcano Santa María which overlooks the active crater from over 1500 meters above. Santiaguito is part of the Central American Volcanic arc located inland from an oceanic trench marking the subduction of the Cocos Plate under the Caribbean Plate. The dacitic dome complex trends east-west and is situated in the 1902 eruption crater of the composite Volcán de Santa María (Rose 1972).

The active Caliente vent has been the only eruptive center since 1977 (Rose 1987; Harris et al. 2003; Johnson et al. 2004; Sahetapy-Engel et al. 2008). Although activity has varied slightly over time, from 2008 to the present it is characterized by blocky lava extrusions from the top of the dome accompanied by explosive vertical ejections of pyroclastic material on the order of once an hour. Collapses of lava flow fronts and vertical eruption columns periodically generate small pyroclastic flows. Blankenbicker (2009) reviews recent descriptions of the volcano's activity.

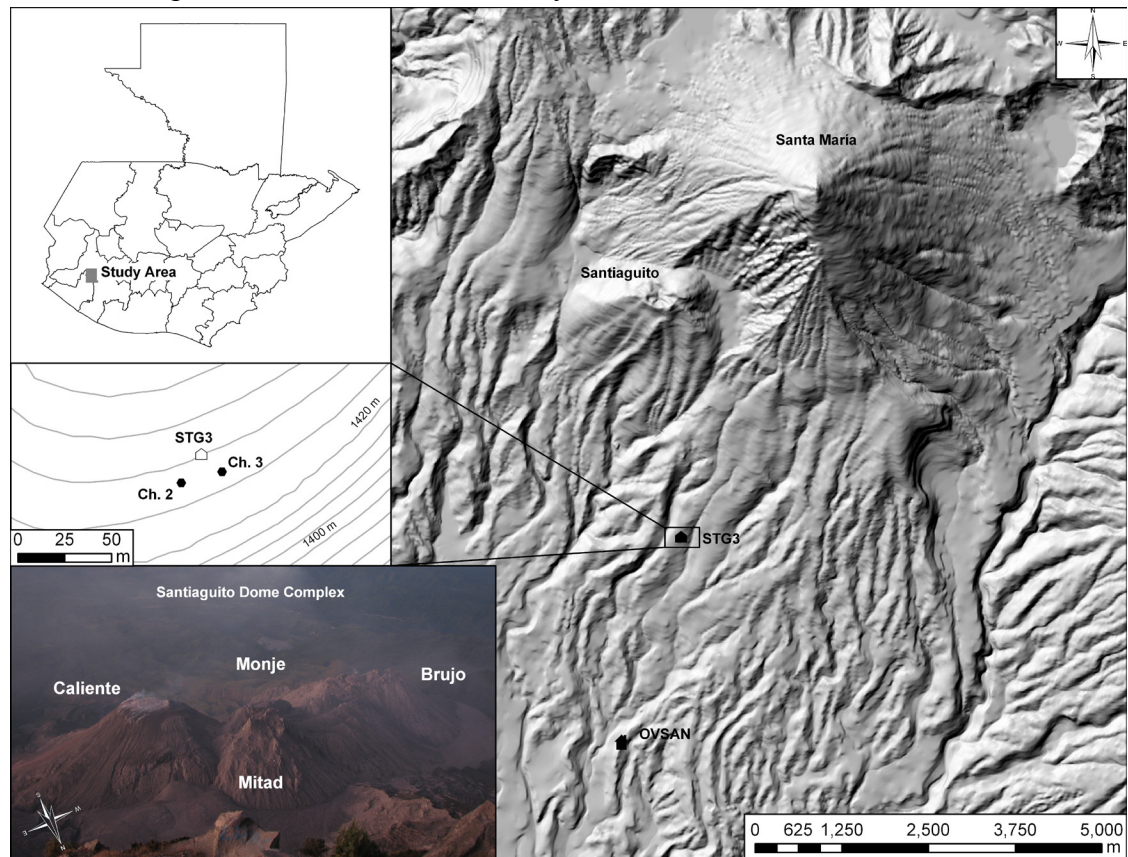


Figure 2.1: Site location and relative location of infrasound microphones.

2.2 Data Collection Period

K.A. Brill lived in Las Marías, an aldea (village) of El Palmar, from April of 2008 until April of 2010 and worked at the Observatorio Volcanologico del Complejo Volcanico Santa María y Santiaguito (OVSAN) operated by the Instituto Nacional de Sismología Vulcanología y Meteorología (INSIVUMEH) of Guatemala as part of a United States Peace Corps assignment. Visual observations conducted during this time were made from OVSAN in three to six hour periods (dawn until visibility was blocked by orographic cloud formation) two to four times a week. Myriad data collection accompanied visual observations depending on the instrument availability and included the following: seismic recordings, thermal images, light-spectra analysis of plumes, time-lapse photography of the dome, and video recordings of activity. The present study only begins to examine this extensive data set.

3 Methods

3.1 Instrumentation

A seismic station consisting of a three-component, Güralp broadband sensor and three ± 250 Pa dynamic range All SensorsTM differential pressure transducers with flat passband above ~ 50 s was located at the INSIVUMEH instrument hut STG-3 (N $14^{\circ}41'03''$, W $91^{\circ}34'42''$; 3,066.5 m south-south-east and $\sim 1,600$ m below the Caliente vent). A RefTek 130 Data Acquisition System sampled the signal from a broadband seismometer at a rate of 100 samples per second from 1 January - 8 January, 19 January - 2 February, 12 February - 14 February, 16 February - 18 February, 13 March - 23 March, 26 March - 27 March, and 6 April - 7 April for a total of approximately 44 days. Logistical difficulties account for the data gaps, and the original 120 second CMG 3T was replaced on 5 January with a 30 second CMG 40T because of an unresponsive vertical channel.

We used Audubon BirdCam cameras with a 5.0 megapixel resolution, fixed aperture $f/2.8$, 52° field of view in time-lapse record mode to capture time-stamped images (2560x1920) of the dome complex during cloud-free daylight hours.



Figure 3.1: View of Santiaguito/Santa María from OVSAN

The cameras began recording images every morning when light conditions were bright enough to trigger the BirdCAM's built-in photocell. The SVO camera was located at the OVSAN observatory. This series of images has a temporal resolution of one image per minute, while the other cameras (SGC, SGE, and SGF) were located around the Santa María crater rim and were recording images once every five minutes. The first images each day were typically taken at approximately 12:00 UTC or 06:00 local time. Time differences between the seismic record and stamps on the images exist because of a lack of time precision available with the cameras' internal clocks and timing should be taken from the seismic records with timestamps from images being more helpful in identifying relative time differences between images recorded by each camera. The images of 57 explosions from different angles help us constrain conditions during seismic activity.

3.2 Observations

Many groups have examined activity at Santiaguito over time periods of days to weeks. These short observation periods tend to highlight specific types of behavior and account for very diverse descriptions and categorizations of activity. Our dataset has the advantage of being contextualized in a two-year-long observation period, which aids interpretations and forces hypotheses to be grounded in a continuum of behavior. The vast majority of activity in the system was centered on the summit vent of the Caliente dome, but we also observed minor rock falls 2-3 times a month from the Santa María scarp as well twice in two years down the southeast flank of the Brujo dome.

We employed several different techniques to identify events for analysis. We began by exploring seismic and acoustic data recorded during times when we had also made visual observations of the volcano, either from the south in the vicinity of OVSAN, or from the summit area of Santa Maria. We expanded this data set of visually observed activity by reviewing image records recorded by the time-lapse cameras throughout the three month seismic equipment deployment. We observed two types of activity at Caliente which generated seismic and acoustic signals, and we classify this activity into two groups: explosions and rock falls. The signals of these events generally shared common frequency domains, and therefore we needed to be able to differentiate these events using more subtle criteria in order to ultimately design efficient automatic detection algorithms.

3.2.1 Explosions

We classify explosions as emissions expelled from the vent at the summit of Caliente dome. Explosions originated from varying locations around the summit, and sometimes displayed a ring-shaped pattern in the initial seconds of an event when viewed from above, but also originated from the center of the vent. Explosions sometimes began impulsively, all at once from the entire summit region and sometimes began emergently from a specific location and expanded out as intensity increased. The emissions varied in

color from white/translucent to grey/opaque depending on the ash content. On several occasions, we saw markedly different color plumes emanating from different parts of the dome summit simultaneously. The explosions were usually audible 3 km from the dome at STG3, and often audible 6 km from the dome at OVSAN. When explosions did contain an audio component, it typically sounded similar to a low pitched jet engine. Explosion columns sometimes collapsed to produce pyroclastic flows down the flanks of the dome which traveled up to a kilometer down slope.

Explosions exhibited a stark contrast from background noise in both the seismic and acoustic channels. The signals either peaked immediately and decayed quickly into the background (impulsive onset) or showed a more emergent onset peaking up to several seconds into the event before decaying (emergent onset). Events often contained multiple signal amplitude peaks and sometimes would decay to background levels briefly within one selfsame event. We classify events as continuous if the signals were separated by background levels for less than 300 seconds due to the inability to visually distinguish the end of one activity peak and the onset of the next. The waveform shapes are consistent with our visual and aural observations.

3.2.2 Rock Falls

Rock falls originated from the top of the dome and also from various points on the dome depending on the location of the lava flow(s). These events occurred several times an hour and could happen simultaneously with or independently from explosion events with a wide range of magnitudes. Travel lengths of the rock fall material as well as the amount of noise emitted from the impacts of the materials correlated directly with the size and amount of material involved.

Rock fall events also showed up in the seismic channels with impulsive and emergent onsets. They were more easily distinguished from explosion events in the acoustic channels due to lower amplitude signals and loss of correlation across the acoustic channels over time as the rocks generating the sources moved down slope. Rock falls were most easily distinguished from tremor events based on their frequency content, as rock fall events did not contain energy in frequencies lower than 2.5 Hz and tremor events did.

4 Analysis and Results

We used observations from the comparison of the seismic and acoustic records with observed surface activity to design an automatic detection algorithm. A Short Term Average / Long Term Average (STA/LTA) ratio picking algorithm identified events in the first acoustic channel in order to eliminate large rock fall events using a root mean squares method; signal to noise ratio of 4:1 to start the pick and 1:1 to stop; and a 2-pole Butterworth band-pass filter from 0.2 – 10 Hz. The author visually checked and corrected the automatically selected events using Antelope's dbpick program, then visually picked the end of each event where the signal decayed back to background levels for more than 10 minutes. This resulted in the identification of a total of 392 explosion events which are catalogued in Appendix 1: Event Catalog. While rock fall events were sometimes contemporaneous with explosion events, rock falls independent of explosions were ignored in this study. Activity occurring within five minutes of any other activity was classified as a single event because breaks shorter than this were indistinguishable in visual observations. Events range in duration from 38 seconds to 1248 seconds, and average 233 seconds with a standard deviation of 173 seconds.

We observe 347 examples of events beginning impulsively from background levels. Many of these signals show multiple amplitude peaks over the course of one event, sometimes decaying to background levels for several tens of seconds in between peaks. We also see 236 events with signals which emerge slowly and gain amplitude over the course of several seconds, taking the form of volcanic tremor. Two hundred three of these tremor events occurred close to or simultaneously with an impulsive event. One hundred thirty one tremor events are harmonic in nature and 52 show harmonics in the infrasound channels. Instances of harmonic tremor occurred before, after, during, and completely independent of impulsive events, and had durations similar to the rest of the events in the data set.

The seismic records of these events have many characteristics that are consistent with our visual observations. Events that start from one part of the summit of the dome and then increase in intensity and expand to other parts of the crater also show increasing amplitudes in the seismic signals over time; events with distinct pulses in the plume also show multiple amplitude peaks in the seismic signal. When comparing the harmonic tremor signal to surface expressions of activity, when there is not an impulsive component to the event, the harmonic tremor is contemporaneous with ash poor, white emissions.

Different components of the signal can shed light on possible source mechanisms, and frequency content is one commonly explored parameter. Similar frequency spectra present in signals across seismic networks reveals much about the source, especially

when viewed in relation to time (Konstantinou and Schlindwein 2003). The higher the resolution in both the time and the frequency domains, the more accurately we can constrain source characteristics, so we explore several analytical techniques to achieve these higher resolutions. Most of the data analysis was done using the GI Seismology MATLAB Object (GISMO) suite from the Geophysical Institute of the Alaska Volcano Observatory at the University of Alaska Fairbanks (Reyes and West 2011).

4.1 Fourier Transforms

We performed short-time window Fourier transforms (STFT) and plotted the resulting spectrograms to analyze the spectral content of the signals. Impulsive onset events tend to have a broadband arrival (typically from 0.2-10 Hz) that quickly decays in amplitude from the higher frequencies down, resulting in a sail shape. Typical harmonic tremor fundamental frequencies are between 0.3 and 0.6 Hz. We took a subset of these events and determined the lowest observed fundamental frequency band to be 0.31 Hz, with spacing between frequency bands of 0.32 Hz – 0.62 Hz and as many as 20 overtones.

Variations in harmonic tremor frequencies with time, a phenomenon that has been called spectral gliding, are common in our data set. Gliding occurs either up or down at the

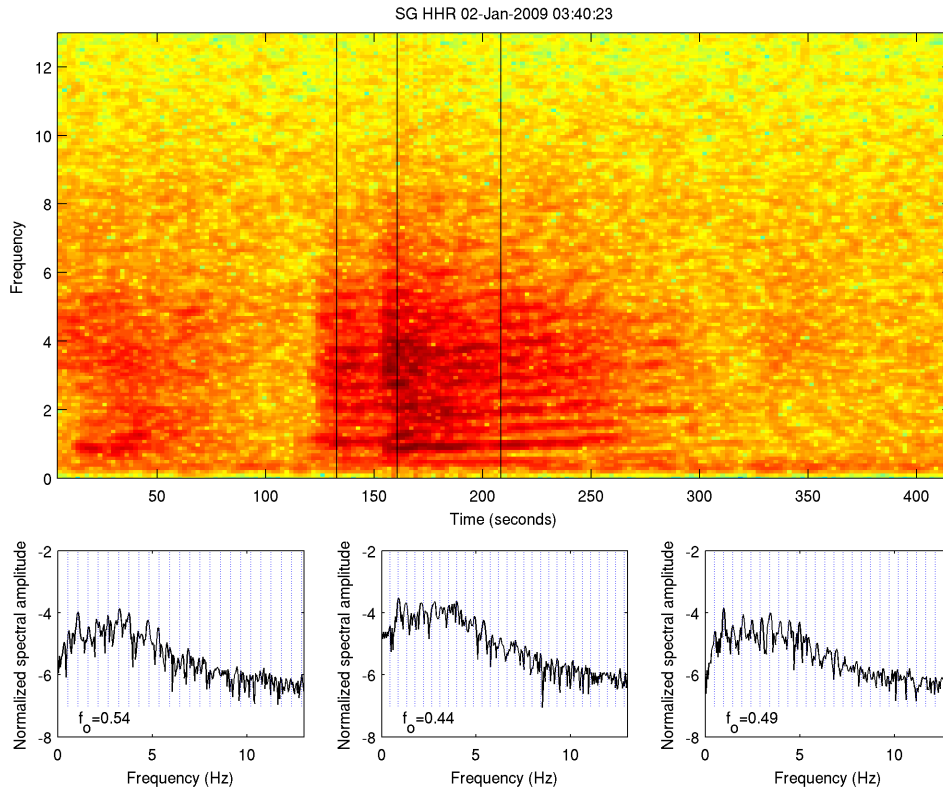


Figure 4.1: STFT spectrogram of the radial component (spectral amplitude in \log_{10}) and dissection windows (length = 10 sec) taken at vertical lines. The dotted lines in spectra windows show integer multiples of fundamental frequency, f_0 .

onset of the tremor, and then up or down as the signal fades away, with separations between frequency peaks increasing for higher overtones. Appendix 3: Representative Events is a list of 10 different representative events: different from each other, but similar to behavior identified throughout the data set. Appendix 4: STFT and Particle Motion consists of STFT plots of the events in Appendix 3: Representative Events with close examinations of frequency content at 5 second time windows, as in Figure 4.1. The fundamental frequency usually has the longest duration, but sometimes is obscured by a background signal. One common manifestation has the signal gliding down at the beginning, and then back up at the end, with higher overtones evolving as the signal continues from the lower frequencies up and then dropping off as the signal decays from the higher frequencies down, exhibiting a triangle shape with upturned edges on each overtone. When different overall amplitude peaks in the traces occur in the middle of one of harmonic tremor, we see the fundamental frequency and spacing between overtones shifted either up or down.

4.2 Wavelet Transform

While the short-time Fourier transform spectrogram provides good resolution in frequency, discrete signals can smear in time giving the appearance of resonance. For example, Lees and Ruiz (2008) showed that closely-spaced, discrete events can mimic harmonic tremor in a spectrogram. With so much temporal variability in the frequency content of the events in our data set, higher temporal resolution would help shed light on features that may link well with source generation. A wavelet transform scalogram provides good temporal resolution, but poor frequency resolution for frequencies farther away from f_0 . We performed a wavelet transform using a complex Morlet wavelet to constrain temporal resolution and verify that tremor was continuous and not composed of discrete pulses. Following Addison (2002), the Morlet wavelet is a complex sinusoid modulated by a Gaussian window function expressed as

$$\psi\left(\frac{t-b}{a}\right) = \frac{1}{\pi^{1/4}} e^{i2\pi f_0[(t-b)/a]} e^{-\frac{1}{2}[(t-b)/a]^2}$$

where t is time, a scales the wavelet, b is a translation of the wavelet in time, and f_0 is the center frequency of the wavelet. A wavelet transform can achieve higher temporal resolution than a Fourier transform by varying not only the scale of the controlled signal but also the time window and center frequency. The choice of the scaling, translation, and center frequencies significantly alter the outcome of the wavelet transform constants as they enhance different aspects of the frequency content of the original signal. We follow convention (Vetterli and Kovacevic 1995; Addison 2002; Lees and Ruiz 2008) and choose a scale factor of one and a center frequency equal to five. Figure 4.2 shows quite

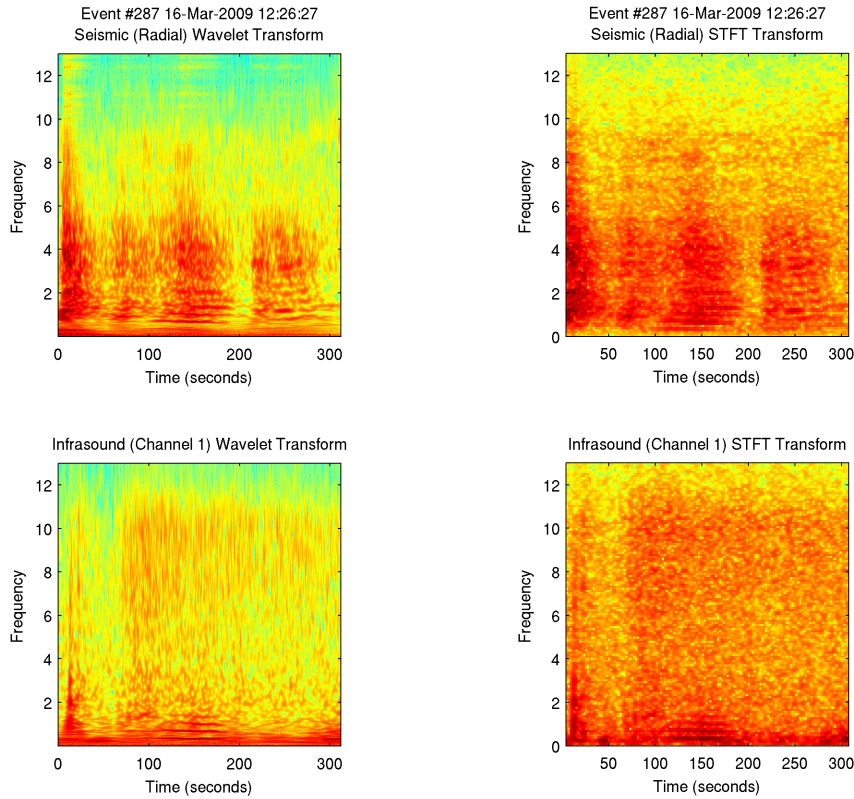


Figure 4.2: Comparison between scalograms from wavelet transform (complex Morlet, $f_0=5$, $a=1$) on the left and spectrogram made from short time Fourier transform (FFT length 10.24 sec)

clearly that these events remain coherent throughout and do not exhibit pulsing which would result from lack of continuity over time.

The wavelet transform does reveal temporal spacing differences in some other events. is a series of plots of wavelet transform scalograms and STFT spectrograms of these 10 events. The increased temporal resolution of these plots helped us to distinguish the presence of multiple types of activity apparently imprinted on top of one another. Along with our observations from images and videos, we infer that that these result from different sources in the conduit.

4.3 Particle Motion

In theory, one should be able to infer characteristics of the source geometry using particle motions. For example, an isotropic spherical source radiates only P waves, a vertical pipe should radiate only P and SV, and a vertical crack could also radiate SH. Furthermore, the body-wave radiation pattern of a crack, could constrain the crack orientation. But in practice, the complex structure of volcanic edifices combined with multiple simultaneous tremor sources makes interpreting particle motions difficult. The complicated nature of recorded volcanic tremor particle motions (Kubotera 1974; Riedesel et al. 1982) lead

Fehler (1983) to conclude that a unique determination of the wave types that compose tremor is not possible. Hellweg (1999b) observed different polarization of particle motion at different frequency bands in the tremor at Lascar Volcano and concluded that it was impossible to distinguish individual wave types or even differentiate whether the motions resulted from source or site effects. Complications arrive from heterogeneous media and rough topography, which scatter and convert waves. While this complicates the signal, particle motions can still be used to investigate source characteristics. For example, the stability of ratios of R/T, R/Z, and T/Z would indicate a stationary, stable source.

Figure 4.3 represents an example of particle motions during an event over three separate five second windows at varying frequency bands (other events can be seen in Appendix 4: STFT and Particle Motion). In this way we capture the range of particle motions at the fundamental frequency of the tremor and the first two overtones and can see the influence of different parts of the signal over time. Particle motions are typically elliptical and cannot be clearly attributed to a single wave type. The dominant horizontal motion is often near 45° from the radial direction indicating that the signal is dominated by body waves. Tsuruga and others (1997) reported similar elliptically rotating tremor particle motions evolving over the course of an event at Sakurajima Volcano and proposed that they resulted from the superposition of other wave types over initial SV-waves.

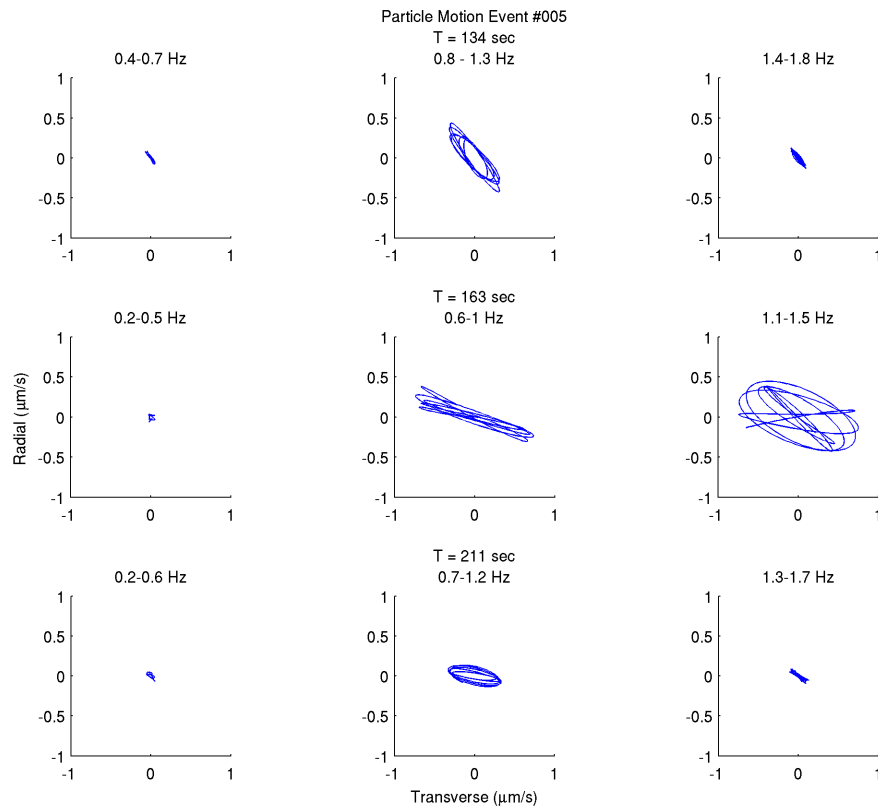


Figure 4.3: Particle motion for five second window filtered at different frequency bands.

In addition to a complex source process, the path from the presumably shallow source location in the dome to the station crosses two valleys and is probably strongly scattered. For example, Rayleigh waves may result from scattering at the free surface and arrive at large angles from the radial direction (e.g., Anderson et al, submitted, 2011).

The near-field and intermediate-field terms, typically ignored in seismology studies, may also influence particle motions at close distances and/or low frequencies. Lokmer and Bean (2010) model the effect of the near-field term on polarization and demonstrate that for distances less than or near to one P-wave wavelength that the near-field amplitude will be comparable to that of the P-wave. Beyond that distance, the near-field and intermediate terms decay faster than the far-field terms components, but are not negligible. In addition, the amplitude decay at a given frequency depends on the source mechanism and could result in varying influence of the near-field terms with frequency. These affects could be strongly influencing the particle motions we are observing between 0.3 and 2 Hz, which correspond to wavelengths of 10 km and 1.5 km for $V_p=3\text{km/s}$, and may explain the variations in particle motions for volcanic tremor at other volcanoes as well (e.g., Hellweg 1999b). A proper investigation of the near-field affects can only be done with numerical modeling and is beyond the scope of this study.

While the source and path affects may be significant, they cannot account for all of the observed variability in particle motions. We attribute at least some of this to a variable source mechanism. Changes in relative amplitudes and particle motion directions over the course of single events, at different frequencies simultaneously, and between events suggest an unstable source over time.

4.4 Energy Partitioning of Events (VASR)

Johnson and Aster (2005) introduced the volcano acoustic-seismic ratio (η , or VASR) in order to quantify the amount of energy released by different events, as well as how that energy is released. They argued that this relationship can give special insight into changing conduit conditions both during an individual explosion and from one explosion to the next. This type of event to event comparison proves useful in aiding our understanding of the dynamics at Santiaguito by demonstrating how events of varying energy magnitudes are related to or different from one another. We will investigate how energy is partitioned over time as well as how it is partitioned in different types of events.

In the acoustic data, we follow the assumptions of isotropic radiation from a monopole point source and calculate the acoustic energy using

$$E_{\text{acoustic}} = \frac{2\pi r^2}{\rho_{\text{atmos}} c_{\text{atmos}}} \int \Delta P(t)^2 dt$$

for one channel of the acoustic data, where r is the distance from the volcano to the microphone (3,066.5 m), ρ_{atmos} is the air density (1.2 kg/m³ at 15°C), c_{atmos} is the speed of sound (340 m/s at 15°C), and $\Delta P(t)$ is the excess pressure as a function of time.

In the seismic traces, by assuming that velocity waveforms represent seismic kinetic energy density at a specific location on the volcano (middle to the top of the dome), we calculate the total seismic energy assuming body wave radiation:

$$E_{\text{seismic}} = 2\pi r^2 \rho_{\text{earth}} c_{\text{earth}} \frac{1}{A} \int S^2 U(t)^2 dt$$

where ρ_{earth} is the volcano density (2000 kg/m³), c_{earth} is the seismic wave speed (2500 m/s) U is the particle velocity, S is the site response (fixed at unity), and A is attenuation (also fixed at unity). For both the seismic and acoustic energy calculations t is the entire length of any event from signal onset until both seismic and acoustic traces have decayed to background. We follow Johnson and Aster's convention of treating seismic energy as pure body waves, assigning a single wave velocity, in spite of the obvious error associated with near-field components and surface-waves that are not properly accounted for. Because of problems with the vertical channel during a portion of the recording interval, we use only the radial channel for energy calculations. Our estimated velocity is somewhere between an average V_p and V_s for the study area.

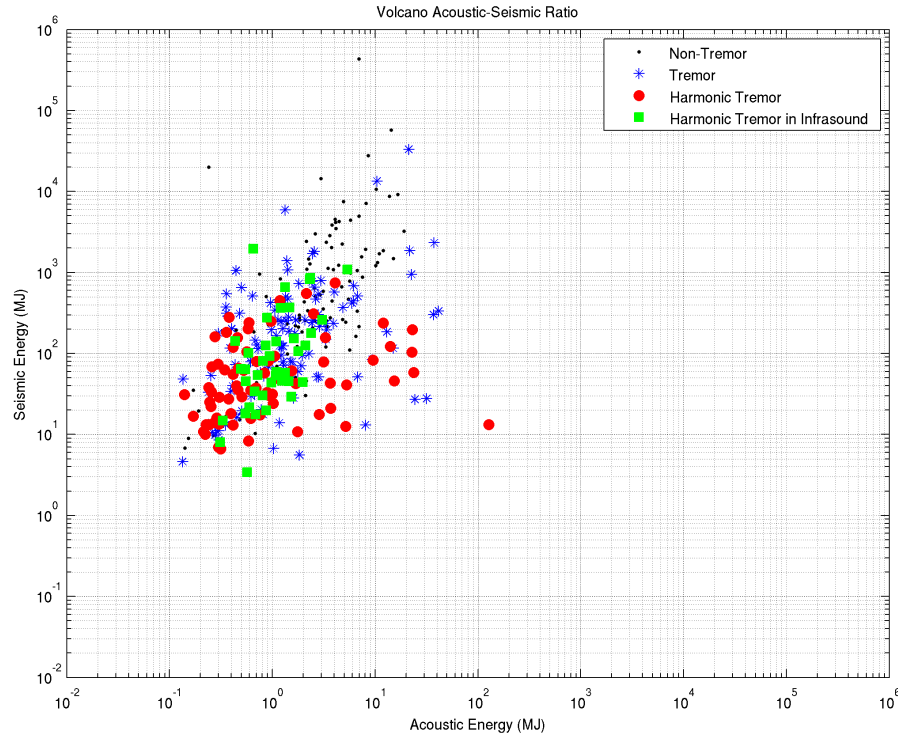


Figure 4.4: VASR of events sorted by class

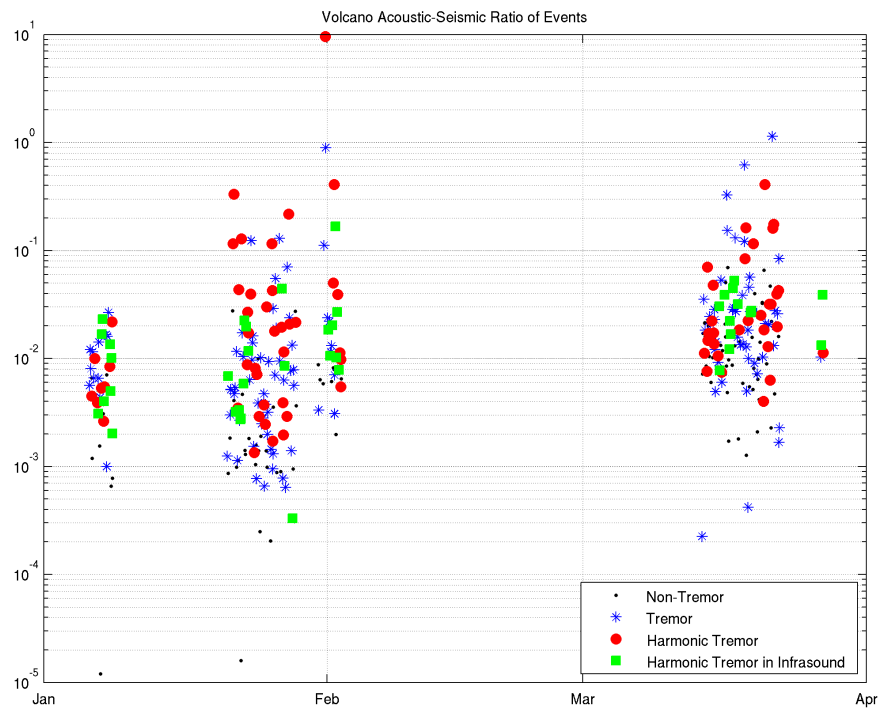


Figure 4.5: VASR of events over observation period sorted by class

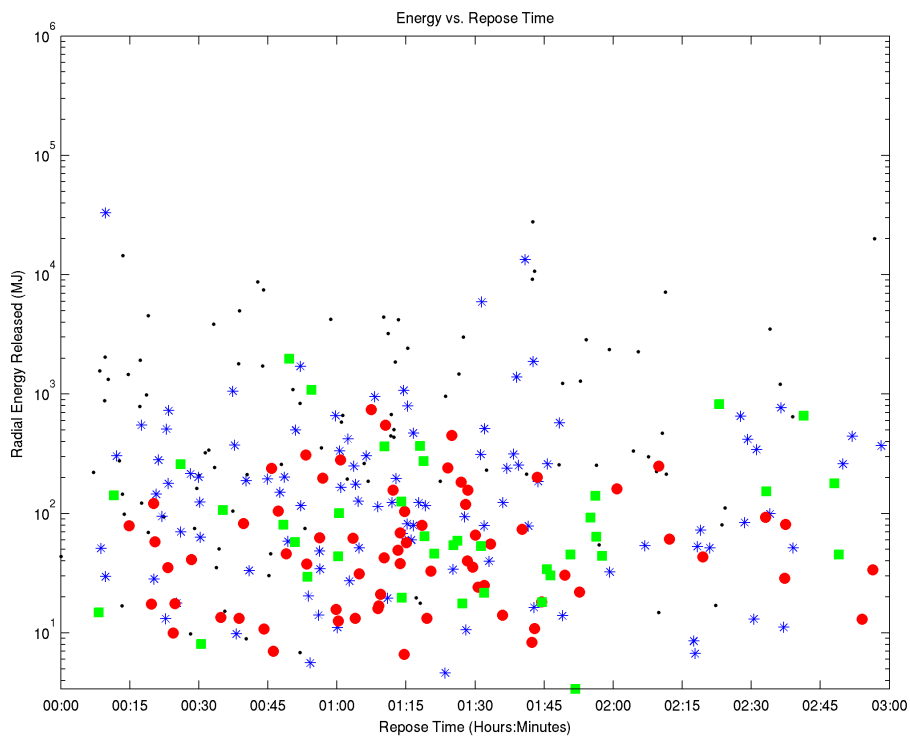


Figure 4.6: Normalized energy of events with time since preceding event

Figure 4.4 shows the seismic and acoustic energy calculated for all of the events in the catalog and Figure 4.5 shows the VASR of each event as a function of time. The overall clustering of the events shows similar distribution to events observed by Johnson and Aster (2005) at Erebus and Karymsky. We use different symbols to differentiate between classes of events. “Non-tremor” events are those events that do not include a tremor component, “tremor” events are those events that did include a tremor component but without any harmonic tremor components, “harmonic tremor” events include those events with harmonic tremor in the seismic channels only, and “harmonic tremor in infrasound” events had a harmonic component which registered in the acoustic sensors as well. Figure 4.6 displays VASR compared with repose time between events (using the same symbols as Figure 4.4).

The striking thing about these events is that they do not seem to show any kind of preferential distribution by class type; events of one class are no more likely to be followed or preceded by any other class in particular, nor are they grouped together by energy release. While we might also draw conclusions about the nature of all of the events, this pattern suggests that a source mechanism for harmonic tremor is either transitory in nature but generated by conditions easily replicated within the system or that the mechanism is only excited by certain conditions not related to the amount of energy released by any given event.

5 Discussion

5.1 Models of Tremor

Here we review several models of harmonic tremor from the literature and look for applications to our observations. Any model must satisfy the observations of harmonic tremor in both the seismic and acoustic records, which suggests the source is well coupled to both the atmosphere and the solid earth.

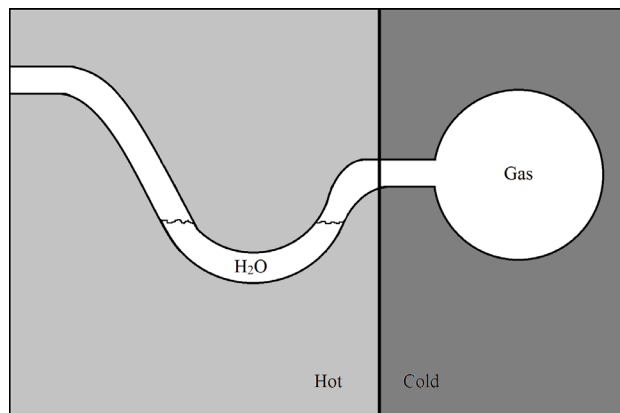


Figure 5.1: Sketch of possible source of thermoacoustic oscillations causing tremor modified after Busse et al. 2005

5.1.1 Thermoacoustic

Hellweg (1999b) presents the possibility of a thermoacoustic oscillator as the source for large, non-linear amplitudes of harmonic tremor observed at Lascar volcano in Chile. This model draws from elementary laws of thermodynamics as well as principles of acoustic engineering: heat

flow from a high temperature source to a low temperature sink generates large

amounts of acoustic energy through spontaneous oscillations of air in a conduit as heat flows from source to sink (Swift 1988). In a volcano, Busse and others (2005) argue that this should be considered as a mechanism for the generation of long-duration harmonic tremor observed at Lascar volcano because of the very high output efficiency of these processes, and the fact that fluid probably present in and around the areas of heat exchange in a volcano would optimize coupling of oscillation frequencies and facilitate thermoacoustic instabilities in relatively small volumes (10-20 m³ resonant chambers).

5.1.2 Magma column “Wagging”

Jellinek and Bercovici (2011) derive a mathematical model for seismic tremor in which a viscous magma column acts like an inverted pendulum. In this model, the column, surrounded by an outer annulus of sheared bubbles, will swing back and forth due to the downward pull of gravity and a restoring force proportioned by a spring effect of the annulus. The model claims to account for both the long or short durations and the relatively small frequency range (0.5 – 7 Hz) of tremor observed at volcanoes around the world.

The frequency of the oscillations (ω_0) are predicted with the relation

$$\omega_0 = \sqrt{\frac{2\rho_0 C^2}{\phi_0 \rho_m (R_c^2 - R_m^2)}}$$

where ρ_0 is the undisturbed gas density [$\sim 25 \text{ kg/m}^3$ (Jellinek and Bercovici 2011)], C is the gas sound speed [700 m/s (Jellinek and Bercovici 2011)], ϕ_0 is the undisturbed gas volume fraction or porosity [70% (Jellinek and Bercovici 2011)], ρ_m is the density of the magma [2500 kg/m³ (Jellinek and Bercovici 2011)], R_c is the conduit radius, and R_m is the magma column radius. The height of the wagging column (H_c) is described as

$$H_c = \frac{\pi}{2} \sqrt{\frac{\mu_m}{2\rho_m \omega_0}}$$

where μ_m is the magma viscosity [$10^8 \text{ Pa s} < \mu_m < 10^{10} \text{ Pa s}$ (Whittington et al. 2009)].

If we solve for $R_c^2 - R_m^2$ in Equation 4 using our observed frequency bands of tremor (0.3 – 5 Hz), the model predicts values from approximately 4000 to 14, the former of which allows for a conduit greater than 120 m in diameter, and the latter of which allows an annulus thickness of less than one meter. The observed frequencies could represent column heights ranging from 99 – 4,055 m in length.

5.1.3 Organ Pipe & Clarinet

Numerous authors have proposed a mechanism similar to organ pipe resonance to explain the evenly spaced peaks often observed in harmonic tremor. The models generally invoke a fluid-filled magma column as a resonator which is closed at the bottom end by an impedance contrast at the depth of bubble nucleation and either closed at the top by some sort of magma plug or open to the atmosphere. These open or closed upper boundary conditions govern which overtones will be present. At Arenal volcano in Costa Rica, Lesage and others (2006) suggested a variation on this organ pipe model where the upper plug is fractured and generates tremor through repeating pressure pulses stabilized over time by feedback mechanisms in the resonating conduit.

5.1.4 Julian

Julian (1994) proposed a model where fluid passing through a constricted channel with elastic walls generates tremor through oscillations of the channel walls and the fluid flow speed. Julian assumes an incompressible fluid (density $\rho = \text{constant}$) flowing through a channel of thickness $h(t)$ and establishes the kinematic relationship that the flow speed averaged over the channel cross section $v(x, t)$ is equal to the channel width at any given time (\dot{h} , where the dot signifies differentiation with respect to time) divide by the initial channel width (h) at a point in the channel (x) subtracted from the flow speed at an arbitrary origin point in the channel (h), or

$$v(x, t) = v(0, t) - \frac{\dot{h}}{h} x$$

Julian continues the model by assuming inviscid flow (low η) and that pressures within the reservoirs at either end of the channel relate to speeds and pressures at the ends of the channel by Bernoulli's theorem (in the form $p + \rho v^2/2 = \text{constant}$) to establish boundary conditions at the end of the channel. By also assuming laminar Hagen-Poiseuille flow, he arrives at the first equation of motion

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

where L is the length in the x direction of the channel. The second equation of motion is relies on conservation of momentum in the channel and how the fluid pressure force (F_p) relates to the elastic/damped response of the channel walls to give

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

These two equations of motion govern the dynamics of the tremor model and make up a third order system of non-linear ordinary differential equations. Julian opts to solve them numerically rather than analytically due to the multitude of different parameters which are interdependent, and goes on to qualitatively describe the equation's behavior.

5.2 Case Studies of Event Suite at Santiaguito

In order to better understand the processes that generate harmonic tremor and which mechanism(s) might best explain our observations, we investigate three consecutive events (#287-289 in catalog of events) on the 16th of March 2009. These events constitute ideal cases to study since they were typical of the explosions observed visually from OVSA (events on the order of once an hour, average event magnitudes, about four hours of visibility), they were recorded by four time-lapse cameras while our seismometer and three microphones were operational, and they include instances of harmonic tremor. Examining these events simultaneously with their photographic, seismic, and acoustic records helps us explain the source of the harmonic tremor and give us insight as to the significance of changing frequency content of tremor as observed elsewhere in our data.

The first of the three events (#287) captured begins at 12:26:27 UTC on March 16, 2009. The ten minutes prior to the event are quiet, with small rock falls visible both in the seismic and acoustic traces as well as the images. The onset of the event is impulsive and presents a stark contrast from the background signal. The acoustic channels two and three are a bit noisy, but the event is still easily identified. The SVO camera recorded the

earliest stage of the event out of all the cameras, and the plume can be seen less than 50 m above the top of the dome (visually estimated using known viewing geometries) with three distinct leading edges. The next images in the continuum show the plume rising steadily, but always with distinct jet-puff forms around the outside base of the plume at the top of the dome. The relatively broadband seismic amplitude wanes after about 30 seconds, then gains amplitude between 0.7 and 1.6 Hz from 50-70 seconds. A constriction is apparent in the plume most clearly in the images two and three minutes into the event. Harmonic tremor begins 80 seconds into the event and the plume becomes whiter in color and more translucent until the event ends after approximately five minutes, at 12:31:39.

The second event (#288) starts impulsively at 13:01:13 and ends by 13:01:55. Of the three events, it is the shortest in duration and smallest in magnitude. The cameras located on the crater rim did not capture the plume from this event at all because it cleared the field of view within the five minute time window. There are two spectral peaks that could be hinting at harmonic tremor, but as the signal is of short duration (less than 20 seconds) and relatively low intensity, it is difficult to classify it conclusively.

The third event (#289) begins at 13:15:16 with an impulsive onset, lasts about 150 seconds and is captured on all cameras. The event starts off with a mushroom-cloud-like, opaque plume and evolves into a lighter colored more uniformly shaped column. The initial set of plume images for this event has the same jet-puff forms around the outside of the crater rim that were present in the first explosion. There is harmonic tremor beginning approximately 60 seconds into the event, apparently at the same time the column has changed from ash rich to ash poor.

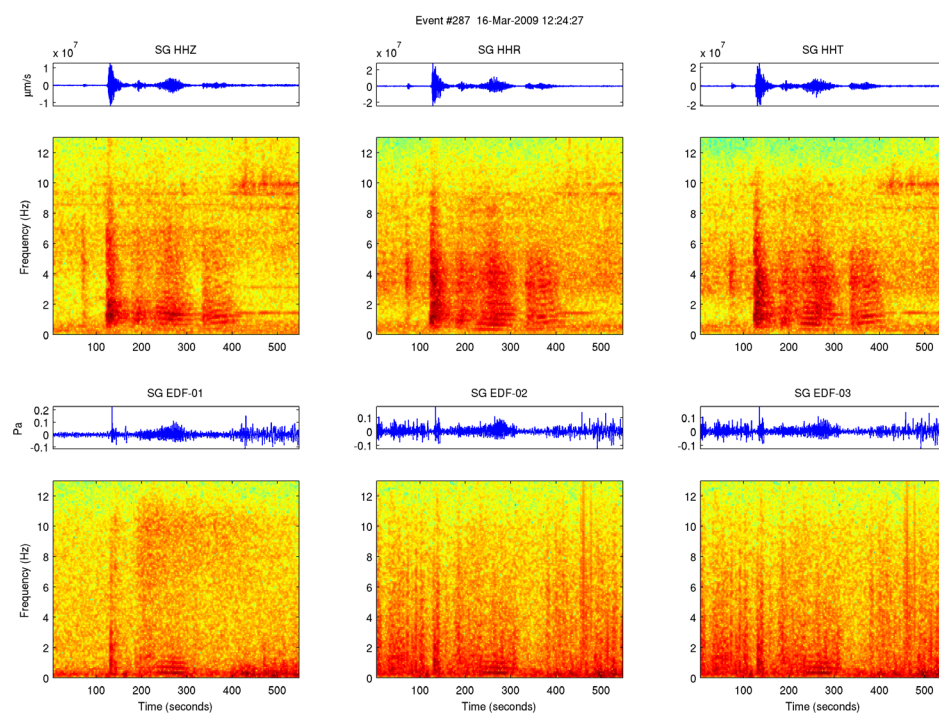
In both instances of harmonic tremor (events 287 and 289) the fundamental frequencies glide upwards several hundredths of a hertz towards the end of the events. In event 287, the tremor cuts out and the gliding begins when the signal resumes 20 seconds later. This gliding appears as the plume is dying out in both events.

5.3 Interpretation of harmonic tremor associated with explosions

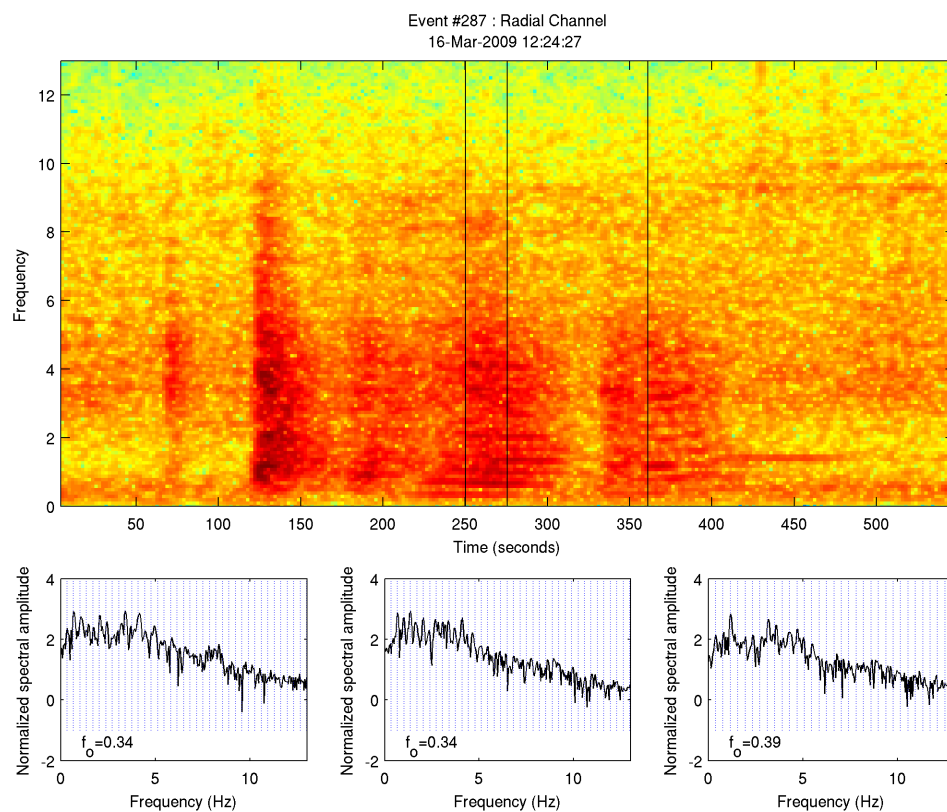
While there are many variations in the characteristic features of the explosions, some features are common within events of specific types. For example, harmonic tremor is coincident with ash poor, white plumes in every instance in which we have visual data concurrent with seismic records. These emissions can occur before, after, during, and independent of more ash-rich emissions, and these emissions also sustain non-harmonic tremor signals as well. The occasional occurrence of coupling to the acoustic signals suggest that the sources of these signals are located in the relatively shallow subsurface. The variability of particle motions and the lack of event class grouping points to changing similar dimensions seems implausible. In this scenario, we would expect to see more

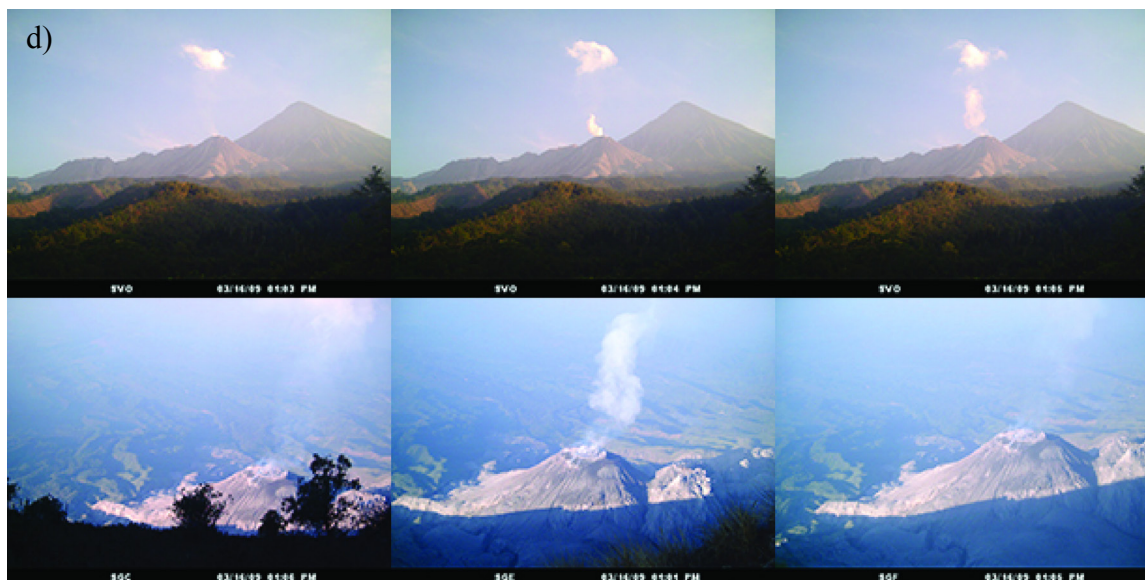


b)

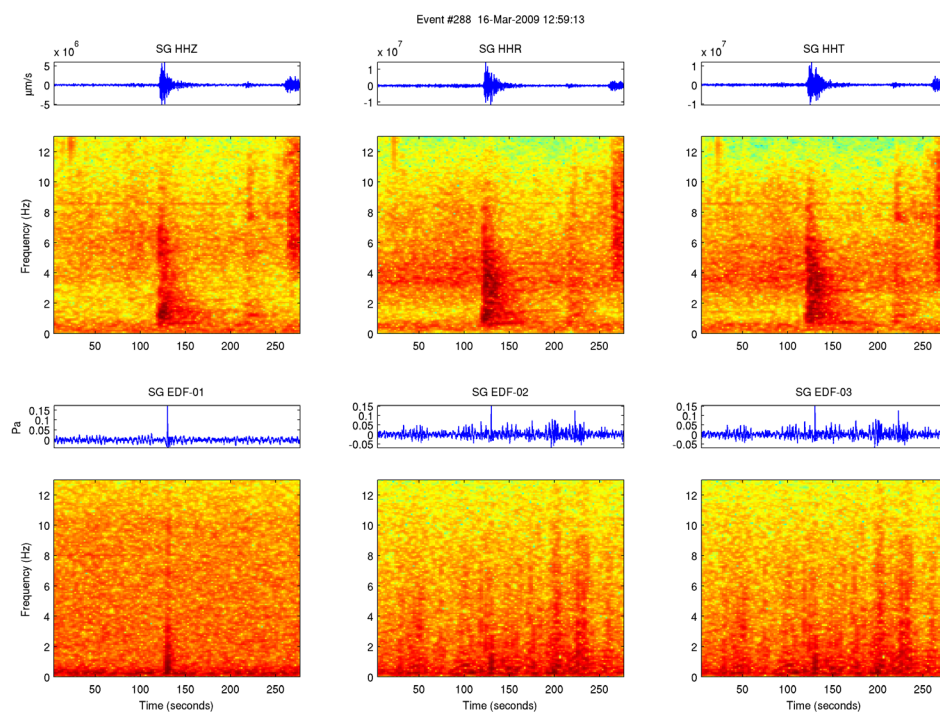


c)



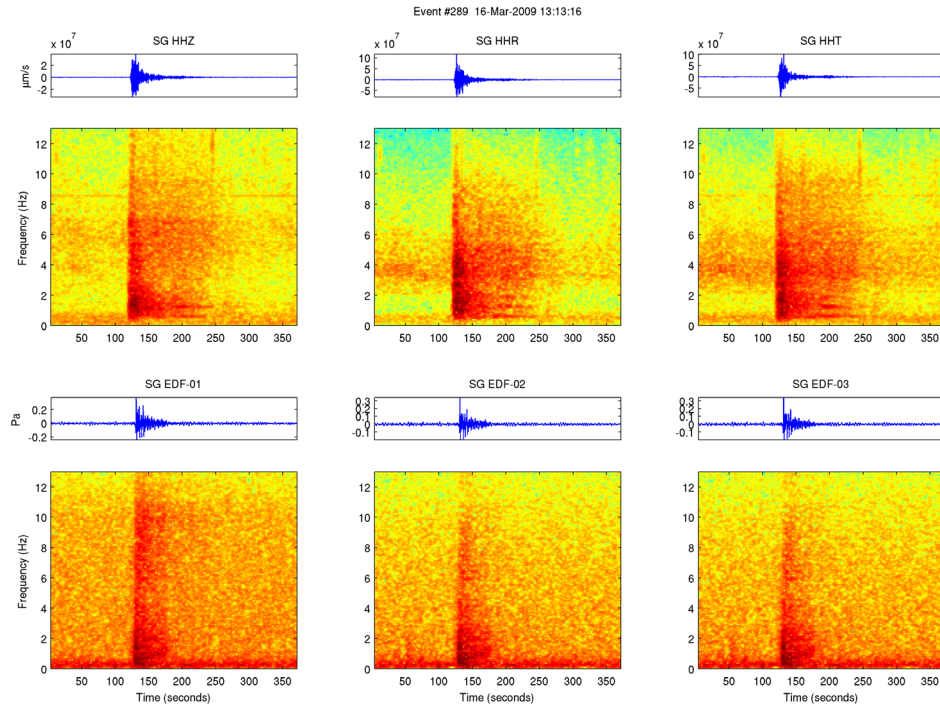


e)





g)



h)

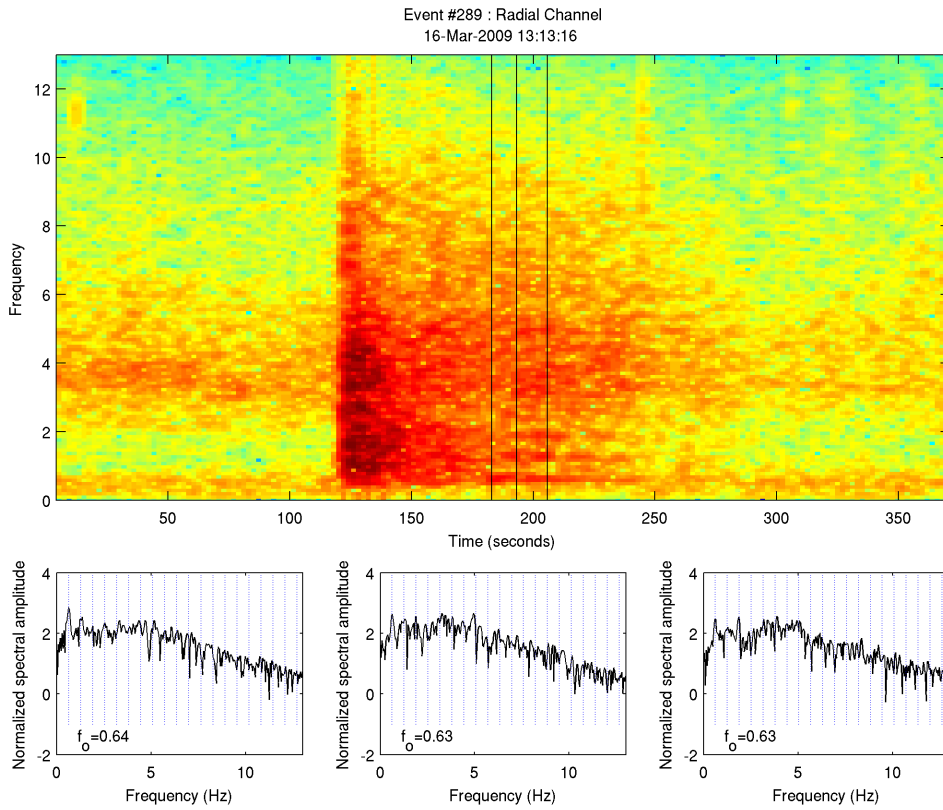


Figure 5.2: a) Time-lapse images of event #287 from cameras SVO, SGC, SGE, and SGF. b) Seismic (HHZ-Vertical, HHR-Radial, HHT-Tangential) and acoustic (Channels 1-3) traces and spectrograms for event #287. c) Radial Channel spectrogram and spectra taken for 10 sec windows starting at vertical lines for event #287. d) Time-lapse images of event #288 from cameras SVO, SGC, SGE, and SGF. e) Seismic (HHZ-Vertical, HHR-Radial, HHT-Tangential) and acoustic (Channels 1-3) traces and spectrograms for event #288. f) Time-lapse images of event #289 from cameras SVO, SGC, SGE, and SGF. g) Seismic (HHZ-Vertical, HHR-Radial, HHT-Tangential) and acoustic (Channels 1-3) traces and spectrograms for event #289. h) Radial Channel spectrogram and spectra taken for 10 sec windows starting at vertical lines for event #289.

simultaneous events exciting such a resonator consecutively over the length of our observation period than we do.

The wagging model predicts frequency gliding in an upward direction with increased eruption intensity due to constriction of the annulus. In our data set we also observed downward frequency gliding, as well as both up and down frequency gliding throughout the course of single events without a large increase in eruption intensity called for by this model (i.e. to Vulcanian or Plinian styles). The timescales of gliding we observe are also inconsistent with the wagging model as described. We observe gliding in multiple directions on the order of seconds, while Jellinek and Bercovici (2011) model gliding that occurs over many minutes. This rapid variation in tremor frequency suggests rapid changes in the conduit system that do not seem plausible at Santiaguito.

The organ pipe/clarinet model presents several problems when we attempt to apply it at Santiaguito. Lesage and others (2006) invoke high impedance contrasts between media within Arenal to explain the resonance. These boundaries trap interface waves within a resonant chamber filled with liquid magma. The seismic waves that are released are mostly surface waves leaving through a fractured cap at the surface, similar to how sound leaves the bell or holes of a clarinet. But the magmatic conditions are very different at Santiaguito. While Arenal has liquid magma in the upper parts of the conduit system, any liquid magma in the Santiaguito system would be too deep in the conduit to provide a resonance chamber that would be simultaneously coupled to the atmosphere. The magma viscosity at Santiaguito is higher than at Arenal ($10^8 - 10^{10}$ Pa s (Whittington et al. 2009) compared with 10^7 Pa s (Cigolini et al. 1984)). Lesage also states that pressure pulses resulting from gas leaks could maintain resonance in the pulse duration was on the order of half an oscillation period, but we have also ruled out short-term pressure perturbations as a source mechanism through our wavelet transform investigations.

The Julian model depends on the fluid in the system being both inviscid and incompressible. The ash-poor gas we observe exiting the system contemporaneous with harmonic tremor does satisfy these conditions from a fluid dynamics stand point. The viscosity of the gas would obviously be near =0, and a fluid can be treated as incompressible as long as the speed of that fluid is much less than the speed of sound in that fluid (Spurk and Aksel 2008). Sahetapy-Engle and others (2008) report near-vent

plume velocities from 16-76 m/s , and Sahetapy-Engle and Harris (2009) recorded temperatures greater than 520 C. The speed of sound at this temperature could be expected to be greater than 500 m/s, so the ash-poor gas would meet the criteria of incompressibility as well.

Holland and others (2011) proposed that explosions at Santiaguito were driven by shear fracturing of the magma at the conduit margins. The magma rises through the conduit, becomes more viscous due to volatile exsolution and rapid crystal growth, and fractures at the conduit margin due to cooling and high strain rates. These small fractures open up into other fractures, generating interconnected networks, and facilitating explosions. The fractures heal or partially heal after the excess pressure is relieved, driving the cyclic nature of the observed events. Passive degassing can be continuous between events through a fractured shallow subsurface that cannot heal due to insufficient heat/pressure, which leads to the development of an unconsolidated fault gouge.

This type of environment would be conducive to generating harmonic tremor via nonlinear excitations of the rock as gas escapes the networks of shear fractures. Differences in how the crack networks heal could account for variability in energy release, timing of events, as well as the incidence of harmonic tremor around different types of activity. Healing and expansion of cracks would change the dimensions of the system during events themselves and could explain frequency gliding frequently seen in the data. If a crack opened up and then lengthened during the course of the event, we could expect a downward glide, whereas if a crack began healing at the end of an event and shortened, we could expect an upward glide.

As shear fracture occurs at depth a fracture network would expand around the magma conduit margin and towards the surface. The gas charged explosion would entrain fine particles as it rose through the system and could emerge on the surface either as one or many points and expand around the margin of the crater. If the carapace is fractured as well, it is possible for these cracks to open as well and explains why some events may seem to originate from the center of the crater.

As cracks are cleared of fine particles during the explosion, there still may be gas escaping from the system out of the established fracture network. These cracks, now clear of debris would be more easily able to resonate with continued gas movement. As long as the paths are open and free of ash, new, possibly less vigorous shear fracture would be able to release gas with these paths already clear, and would account for the emergent events we have observed between more impulsive explosions.

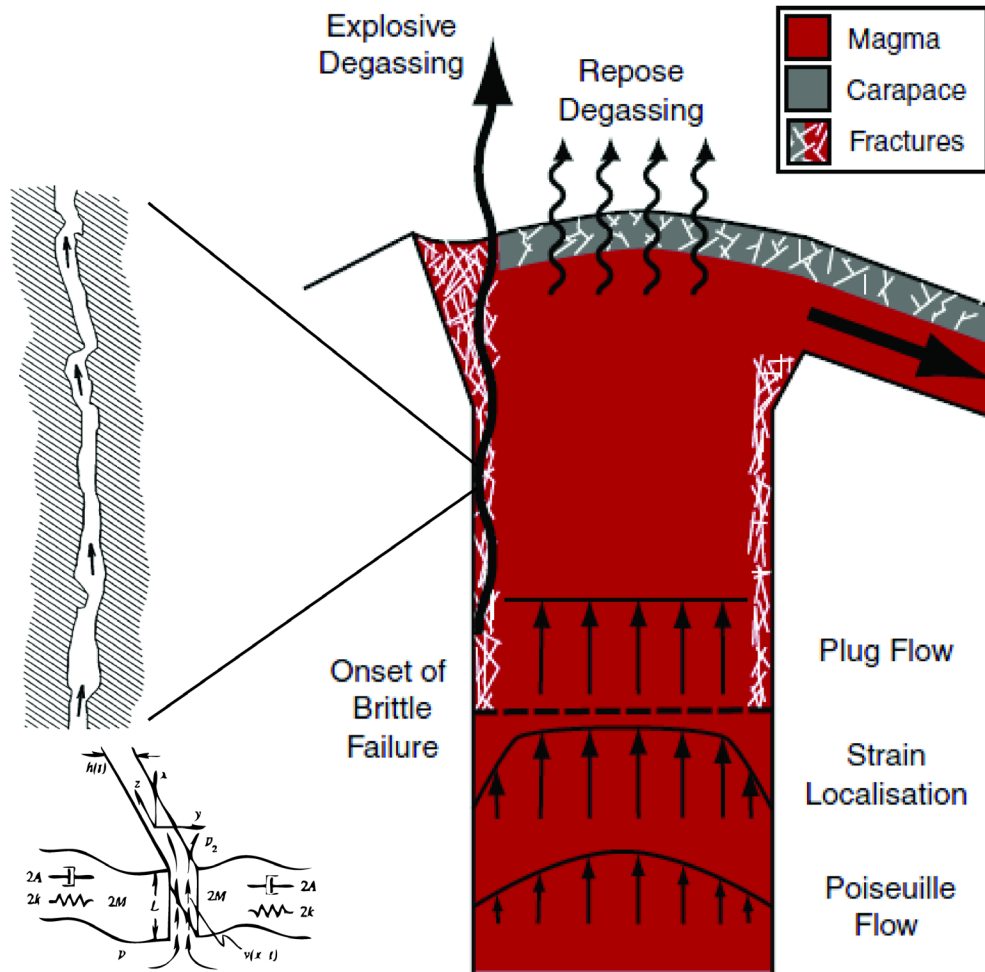


Figure 5.3: Schematic diagram of source mechanism for harmonic tremor modified from Holland et al. (2011) and Julian(1994).

One of the main critiques of the Julian model has been unreasonable fluid speeds needed to generate tremor. At Kilauea for example, deep harmonic tremor would require flow velocities on the order of 45-110 m/s (Julian 1994). Rust and others (2008) built analogue models to explore feasibility of flow through channels. They found that flow speeds on the order of 30 m/s through channels about 100 m long can produce tremor with fundamental frequencies of 0.3 Hz. Sahetapy-Engle and others (2008) calculated exit velocities of 16-76 m/s (averaging 40 m/s), which would be well within the plausible range to generate harmonic tremor as observed at Santiaguito.

6 Conclusions

The harmonic tremor observed at Santiaguito volcano in Guatemala from January to March, 2009 exhibited several unique characteristics. It occurred repeatedly over the observation period, was temporally continuous over periods of 30-200 seconds, and displayed spectral gliding of the frequency peaks at integer multiples (and occasionally demonstrated non-integer multiples as well). Overall event magnitude is not well correlated to between event repose time, arguing against pressurization of a shallow gas reservoir as a driving mechanism for these explosions. Rather, the system is likely more leaky, allowing gas to escape between eruptions. Particle motions are elliptical, irregular, and change polarity depending on frequency and over the course of individual events. These changes are possibly contributions from the near-field terms and/or topographic influences, and point to an unstable source mechanism. Harmonic tremor was contemporaneous with emissions of ash-poor, white colored plumes, and not observed with ash-rich, grey plumes.

These characteristics are explained by a model of fluid (ash-poor gas mixture) passing through a constricted channel with elastic walls (cracks on the order of 100 m long around a central magma plug) generating tremor through oscillations of the channel walls as proposed by Julian (1994). Crack networks are created by shear fracture and the walls resonate as gas rises from deeper in the system (Holland et al. 2011)

This type of mechanism accounts for many of our observations over the two year period from March 2008-March 2010 such as differing plume characteristics at different points of the surface of the dome, as well as characteristics of particle motions which do not support sources stable over time or space. Future work needs to examine these particle motions in greater depth with respect to near-field and intermediate-field terms to better constrain source locations and processes.

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8 Appendix A: Event Catalog

Table 8.1: Events from January - March, 2009

T = Tremor Events, H = Harmonic Tremor Events, A = Harmonic Tremor Events Coupled to the Acoustic

#	Start Time	End Time	Duration	Repose	T	H	A
1	01/01/2009 07:11:28.17	01/01/2009 07:08:33.13	0:04:34.73		0	0	0
2	01/01/2009 20:47:28.35	01/01/2009 20:48:06.60	0:00:38.25	3:56:18.76	0	0	0
3	01/02/2009 00:44:25.36	01/02/2009 00:49:46.46	0:05:21.10	1:45:44.87	1	1	0
4	01/02/2009 02:35:31.33	01/02/2009 02:37:34.20	0:02:02.87	1:04:49.05	1	1	1
5	01/02/2009 03:42:23.25	01/02/2009 03:45:25.24	0:03:01.99	1:19:18.34	1	1	1
6	01/02/2009 05:04:43.58	01/02/2009 05:06:47.61	0:02:04.03	2:34:02.76	0	0	0
7	01/02/2009 07:40:50.37	01/02/2009 07:45:18.14	0:04:27.77	1:42:37.93	0	0	0
8	01/02/2009 09:27:56.07	01/02/2009 09:29:12.58	0:01:16.51	1:00:53.89	0	0	0
9	01/02/2009 10:30:06.47	01/02/2009 10:33:40.92	0:03:34.45	1:09:02.68	1	0	0
10	01/02/2009 11:42:43.60	01/02/2009 11:44:07.06	0:01:23.46	2:09:54.96	0	0	0
11	01/02/2009 13:54:02.02	01/02/2009 14:05:10.88	0:11:08.86	0:11:35.60	1	1	1
12	01/02/2009 14:16:46.47	01/02/2009 14:17:52.55	0:01:06.07	5:18:09.21	0	0	0
13	01/02/2009 19:36:01.75	01/02/2009 19:37:17.10	0:01:15.35	3:28:33.14	0	0	0
14	01/02/2009 23:05:50.24	01/02/2009 23:08:24.42	0:02:34.17	1:00:57.28	0	0	0
15	01/03/2009 00:09:21.69	01/03/2009 00:11:22.83	0:02:01.14	0:14:38.35	0	0	0
16	01/03/2009 00:26:01.18	01/03/2009 00:28:28.39	0:02:27.22	2:49:54.29	1	0	0
17	01/03/2009 03:18:22.68	01/03/2009 03:22:42.34	0:04:19.66	2:56:43.70	1	1	0
18	01/03/2009 06:19:26.04	01/03/2009 06:20:30.95	0:01:04.91	0:47:12.70	0	0	0
19	01/03/2009 07:07:43.65	01/03/2009 07:09:05.96	0:01:22.30	1:14:02.74	1	1	0
20	01/03/2009 08:23:08.70	01/03/2009 08:25:13.89	0:02:05.19	0:50:56.63	0	0	0
21	01/03/2009 09:16:10.53	01/03/2009 09:17:56.01	0:01:45.49	4:31:24.11	1	0	0
22	01/03/2009 13:49:20.12	01/03/2009 13:51:26.47	0:02:06.35	1:24:52.68	0	0	0
23	01/03/2009 15:16:19.15	01/03/2009 15:19:26.94	0:03:07.79	3:01:48.15	0	0	0
24	01/03/2009 18:21:15.09	01/03/2009 18:23:00.58	0:01:45.49	1:18:05.42	0	0	0
25	01/03/2009 19:41:06.00	01/03/2009 19:42:06.28	0:01:00.28	1:07:27.11	0	0	0
26	01/03/2009 20:49:33.38	01/03/2009 20:51:53.64	0:02:20.26	4:13:25.19	1	0	0
27	01/04/2009 01:05:18.83	01/04/2009 01:08:40.53	0:03:21.70	2:36:15.62	1	0	0
28	01/04/2009 03:44:56.15	01/04/2009 03:51:37.23	0:06:41.08	1:39:00.37	1	1	0
29	01/04/2009 05:30:37.60	01/04/2009 05:34:46.83	0:04:09.23	1:01:16.47	1	0	0
30	01/04/2009 06:36:03.29	01/04/2009 06:42:17.71	0:06:14.42	3:10:39.40	1	0	0
31	01/04/2009 09:52:57.11	01/04/2009 09:54:06.66	0:01:09.55	0:22:45.19	0	0	0
32	01/04/2009 10:16:51.85	01/04/2009 10:18:14.16	0:01:22.30	1:03:26.79	0	0	0
33	01/04/2009 11:21:40.95	01/04/2009 11:22:20.36	0:00:39.41	2:48:01.03	0	0	0
34	01/04/2009 14:10:21.39	01/04/2009 14:12:41.65	0:02:20.26	0:54:28.24	0	0	0
35	01/04/2009 15:07:09.89	01/04/2009 15:08:43.79	0:01:33.89	0:43:59.32	0	0	0
36	01/04/2009 15:52:43.11	01/04/2009 15:54:54.10	0:02:10.99	0:48:25.02	0	0	0

#	Start Time	End Time	Duration	Repose	T	H	A
37	01/04/2009 16:43:19.12	01/04/2009 16:44:50.70	0:01:31.58	1:13:15.56	0	0	0
38	01/04/2009 17:58:06.26	01/04/2009 18:00:21.88	0:02:15.63	2:41:24.59	0	0	0
39	01/04/2009 20:41:46.47	01/04/2009 20:42:53.70	0:01:07.23	1:23:37.02	0	0	0
40	01/04/2009 22:06:30.72	01/04/2009 22:09:09.53	0:02:38.81	1:32:03.75	1	0	0
41	01/04/2009 23:41:13.28	01/04/2009 23:44:05.83	0:02:52.55	3:05:25.55	1	1	1
42	01/05/2009 02:49:31.38	01/05/2009 02:56:27.53	0:06:56.15	1:27:26.49	1	1	1
43	01/05/2009 04:23:54.02	01/05/2009 04:26:39.79	0:02:45.77	0:09:38.19	0	0	0
44	01/05/2009 04:36:17.97	01/05/2009 04:37:48.39	0:01:30.42	1:16:34.95	0	0	0
45	01/05/2009 05:54:23.34	01/05/2009 05:56:05.35	0:01:42.01	3:57:03.74	0	0	0
46	01/05/2009 09:53:09.09	01/05/2009 09:55:11.97	0:02:02.87	0:21:13.68	0	0	0
47	01/05/2009 10:16:25.65	01/05/2009 10:17:13.18	0:00:47.53	3:50:13.65	0	0	0
48	01/05/2009 14:07:26.83	01/05/2009 14:10:41.58	0:03:14.74	0:56:56.10	0	0	0
49	01/05/2009 15:07:37.67	01/05/2009 15:09:31.27	0:01:53.60	0:48:58.20	1	1	0
50	01/05/2009 15:58:29.47	01/05/2009 15:59:32.07	0:01:02.60	2:09:25.76	0	0	0
51	01/05/2009 18:08:57.83	01/05/2009 18:09:55.79	0:00:57.96	0:20:44.30	0	0	0
52	01/05/2009 18:30:40.09	01/05/2009 18:33:13.11	0:02:33.01	1:39:26.74	0	0	0
53	01/05/2009 20:12:39.84	01/05/2009 20:18:28.76	0:05:48.92	1:18:48.98	1	0	0
54	01/05/2009 21:37:17.74	01/05/2009 21:39:46.12	0:02:28.38	1:25:10.94	1	0	0
55	01/05/2009 23:04:57.06	01/05/2009 23:08:15.28	0:03:18.22	1:13:21.77	1	1	1
56	01/06/2009 00:21:37.05	01/06/2009 00:25:19.62	0:03:42.57	1:38:20.43	1	0	0
57	01/06/2009 02:03:40.05	01/06/2009 02:07:34.21	0:03:54.16	1:27:57.13	1	0	0
58	01/06/2009 03:35:31.34	01/06/2009 03:38:46.09	0:03:14.74	2:11:20.00	1	0	0
59	01/06/2009 05:50:06.09	01/06/2009 05:54:33.86	0:04:27.77	0:19:42.32	1	1	0
60	01/06/2009 06:14:16.18	01/06/2009 06:16:36.45	0:02:20.26	1:10:20.06	0	0	0
61	01/06/2009 07:26:56.51	01/06/2009 07:28:10.70	0:01:14.19	0:51:02.49	0	0	0
62	01/06/2009 08:19:13.19	01/06/2009 08:22:39.53	0:03:26.34	3:04:31.02	1	0	0
63	01/06/2009 11:27:10.55	01/06/2009 11:33:33.09	0:06:22.53	2:23:03.61	1	0	0
64	01/06/2009 13:56:36.69	01/06/2009 14:11:40.86	0:15:04.17	6:54:16.39	1	1	0
65	01/06/2009 21:05:57.25	01/06/2009 21:18:35.37	0:12:38.11	1:49:00.57	1	1	0
66	01/06/2009 23:07:35.93	01/06/2009 23:13:34.13	0:05:58.19	0:28:22.20	1	1	1
67	01/06/2009 23:41:56.32	01/06/2009 23:44:31.65	0:02:35.33	1:12:21.00	1	0	0
68	01/07/2009 00:56:52.65	01/07/2009 00:59:50.01	0:02:57.36	0:44:55.18	1	0	0
69	01/07/2009 01:44:47.36	01/07/2009 01:55:50.42	0:11:03.06	1:11:56.79	0	0	0
70	01/07/2009 03:07:47.21	01/07/2009 03:09:09.52	0:01:22.30	1:00:27.76	0	0	0
71	01/07/2009 04:09:37.27	01/07/2009 04:12:25.36	0:02:48.08	1:00:16.62	1	0	0
72	01/07/2009 05:12:41.97	01/07/2009 05:15:30.06	0:02:48.08	1:59:09.57	0	0	0
73	01/07/2009 07:14:39.63	01/07/2009 07:19:22.48	0:04:42.84	1:10:06.04	1	1	0
74	01/07/2009 08:29:28.52	01/07/2009 08:33:58.61	0:04:30.09	1:45:38.78	1	1	1
75	01/07/2009 10:19:37.39	01/07/2009 10:26:33.54	0:06:56.15	1:18:29.36	1	1	1
76	01/07/2009 11:45:02.90	01/07/2009 11:46:49.55	0:01:46.65	1:20:22.25	0	0	0
77	01/07/2009 13:07:11.80	01/07/2009 13:09:14.68	0:02:02.87	0:23:14.51	1	1	0

#	Start Time	End Time	Duration	Repose	T	H	A
78	01/07/2009 13:32:29.18	01/07/2009 13:33:39.89	0:01:10.71	0:26:04.58	0	0	0
79	01/07/2009 13:59:44.47	01/07/2009 14:04:12.25	0:04:27.77	1:52:49.56	1	1	1
80	01/07/2009 15:57:01.81	01/07/2009 15:58:56.57	0:01:54.76	3:30:39.87	1	1	0
81	01/07/2009 19:29:36.44	01/07/2009 19:32:46.55	0:03:10.11	1:08:52.55	1	0	0
82	01/07/2009 20:41:39.10	01/07/2009 20:42:55.61	0:01:16.51	0:40:27.07	0	0	0
83	01/07/2009 21:23:22.68	01/07/2009 21:26:25.83	0:03:03.15	0:14:50.55	1	0	0
84	01/07/2009 21:41:16.38	01/07/2009 21:46:27.05	0:05:10.66	1:00:35.44	0	0	0
85	01/07/2009 22:47:02.49	01/07/2009 22:48:15.52	0:01:13.03	3:17:15.99	1	0	0
86	01/08/2009 02:05:31.50	01/08/2009 02:09:59.28	0:04:27.77	2:51:54.20	1	0	0
87	01/08/2009 05:01:53.47	01/08/2009 05:07:21.53	0:05:28.05	1:16:36.52	1	1	0
88	01/08/2009 06:23:58.05	01/08/2009 06:29:44.65	0:05:46.60	0:51:57.57	1	1	1
89	01/08/2009 07:21:42.22	01/08/2009 07:24:36.10	0:02:53.88	1:31:14.91	1	1	1
90	01/08/2009 08:55:51.01	01/08/2009 08:57:02.88	0:01:11.87	1:00:46.22	0	0	0
91	01/08/2009 09:57:49.10	01/08/2009 10:05:28.14	0:07:39.04	0:53:10.49	1	1	1
92	01/08/2009 10:58:38.63	01/08/2009 11:04:43.78	0:06:05.15	0:58:36.64	1	1	0
93	01/08/2009 12:03:20.42	01/08/2009 12:07:11.10	0:03:50.68	0:42:49.25	1	1	1
94	01/08/2009 12:50:00.68	01/08/2009 12:59:55.35	0:09:54.67	2:27:38.28	0	0	0
95	01/21/2009 02:16:17.89	01/21/2009 02:18:52.06	0:02:34.17	1:30:03.82	1	0	0
96	01/21/2009 03:48:55.88	01/21/2009 03:52:23.38	0:03:27.50	0:59:43.07	1	1	1
97	01/21/2009 04:52:06.45	01/21/2009 04:53:29.91	0:01:23.46	4:04:37.05	0	0	0
98	01/21/2009 08:58:06.96	01/21/2009 08:59:21.15	0:01:14.19	0:38:49.43	0	0	0
99	01/21/2009 09:38:12.42	01/21/2009 09:51:33.43	0:13:21.00	1:28:23.52	1	0	0
100	01/21/2009 11:19:56.95	01/21/2009 11:25:05.30	0:05:08.35	0:07:08.99	1	0	0
101	01/21/2009 11:32:14.29	01/21/2009 11:38:35.66	0:06:21.38	4:12:38.49	1	0	0
102	01/21/2009 15:51:14.15	01/21/2009 15:53:08.91	0:01:54.76	1:11:44.58	0	0	0
103	01/21/2009 17:04:53.49	01/21/2009 17:13:59.47	0:09:05.98	1:36:55.65	1	1	0
104	01/21/2009 18:50:55.12	01/21/2009 19:02:08.62	0:11:13.49	0:23:28.74	1	1	0
105	01/21/2009 19:25:37.35	01/21/2009 19:27:17.04	0:01:39.69	0:56:11.71	0	0	0
106	01/21/2009 20:23:28.75	01/21/2009 20:26:42.34	0:03:13.59	2:38:56.98	1	0	0
107	01/21/2009 23:05:39.32	01/21/2009 23:07:05.10	0:01:25.78	1:13:43.57	1	0	0
108	01/22/2009 00:20:48.67	01/22/2009 00:26:52.66	0:06:03.99	2:06:55.46	1	1	1
109	01/22/2009 02:33:48.13	01/22/2009 02:36:45.48	0:02:57.36	0:17:30.59	1	0	0
110	01/22/2009 02:54:16.07	01/22/2009 02:55:19.83	0:01:03.76	1:24:05.55	0	0	0
111	01/22/2009 04:19:25.38	01/22/2009 04:27:18.33	0:07:52.95	1:15:22.28	1	0	0
112	01/22/2009 05:42:40.61	01/22/2009 05:48:33.01	0:05:52.40	0:38:36.64	1	1	0
113	01/22/2009 06:27:09.65	01/22/2009 06:28:21.52	0:01:11.87	1:49:29.35	0	0	0
114	01/22/2009 08:17:50.87	01/22/2009 08:27:00.33	0:09:09.46	0:33:10.68	1	1	0
115	01/22/2009 09:00:11.01	01/22/2009 09:05:27.47	0:05:16.46	0:48:35.06	1	1	1
116	01/22/2009 09:54:02.53	01/22/2009 09:57:13.79	0:03:11.27	2:36:26.43	1	0	0
117	01/22/2009 12:33:40.23	01/22/2009 12:40:39.86	0:06:59.63	1:04:02.75	1	1	1
118	01/22/2009 13:44:42.61	01/22/2009 13:50:09.50	0:05:26.89	0:13:29.45	1	1	1

#	Start Time	End Time	Duration	Repose	T	H	A
119	01/22/2009 14:03:38.95	01/22/2009 14:05:31.40	0:01:52.44	0:52:02.43	0	0	0
120	01/22/2009 14:57:33.82	01/22/2009 14:58:56.13	0:01:22.30	0:39:39.11	0	0	0
121	01/22/2009 15:38:35.23	01/22/2009 15:43:56.33	0:05:21.10	1:30:40.20	1	1	0
122	01/22/2009 17:14:36.53	01/22/2009 17:16:32.45	0:01:55.92	0:37:46.55	0	0	0
123	01/22/2009 17:54:19.00	01/22/2009 17:56:33.47	0:02:14.47	2:00:47.38	1	0	0
124	01/22/2009 19:57:20.84	01/22/2009 19:59:16.76	0:01:55.92	1:14:30.85	1	0	0
125	01/22/2009 21:13:47.61	01/22/2009 21:18:01.48	0:04:13.86	1:23:29.18	1	1	1
126	01/22/2009 22:41:30.66	01/22/2009 22:53:22.40	0:11:51.75	1:22:26.85	1	1	1
127	01/23/2009 00:28:16.37	01/23/2009 00:29:47.95	0:01:31.58	1:08:50.30	0	0	0
128	01/23/2009 01:38:38.25	01/23/2009 01:40:36.49	0:01:58.24	1:48:19.24	0	0	0
129	01/23/2009 03:28:55.73	01/23/2009 03:37:16.50	0:08:20.77	2:20:58.28	1	1	1
130	01/23/2009 05:58:14.78	01/23/2009 06:03:50.95	0:05:36.17	1:41:33.75	1	1	0
131	01/23/2009 07:45:24.70	01/23/2009 07:51:08.99	0:05:44.28	1:15:21.96	1	1	0
132	01/23/2009 09:06:30.95	01/23/2009 09:14:41.29	0:08:10.34	0:52:09.34	1	1	0
133	01/23/2009 10:06:50.63	01/23/2009 10:12:36.07	0:05:45.44	0:30:10.28	1	1	1
134	01/23/2009 10:42:46.35	01/23/2009 10:43:51.27	0:01:04.91	0:19:02.15	0	0	0
135	01/23/2009 11:02:53.41	01/23/2009 11:04:33.10	0:01:39.69	1:35:58.46	0	0	0
136	01/23/2009 12:40:31.56	01/23/2009 12:44:34.99	0:04:03.43	1:14:07.05	1	0	0
137	01/23/2009 13:58:42.04	01/23/2009 14:00:50.71	0:02:08.67	1:10:28.87	0	0	0
138	01/23/2009 15:11:19.58	01/23/2009 15:20:10.49	0:08:50.91	1:40:50.94	1	1	0
139	01/23/2009 17:01:01.43	01/23/2009 17:07:20.49	0:06:19.06	1:26:56.74	1	0	0
140	01/23/2009 18:34:17.23	01/23/2009 18:36:18.95	0:02:01.72	1:52:39.85	1	0	0
141	01/23/2009 20:28:58.80	01/23/2009 20:35:07.42	0:06:08.62	0:29:54.04	1	0	0
142	01/23/2009 21:05:01.46	01/23/2009 21:11:04.29	0:06:02.83	1:56:21.19	1	0	0
143	01/23/2009 23:07:25.72	01/23/2009 23:11:03.65	0:03:37.93	0:09:44.77	0	0	0
144	01/23/2009 23:20:48.42	01/23/2009 23:24:12.44	0:03:24.02	1:43:27.60	1	0	0
145	01/24/2009 01:07:40.03	01/24/2009 01:16:58.77	0:09:18.73	1:43:42.35	1	1	0
146	01/24/2009 03:00:41.11	01/24/2009 03:04:07.45	0:03:26.34	1:14:40.32	1	1	0
147	01/24/2009 04:18:47.77	01/24/2009 04:19:55.01	0:01:07.23	1:12:10.65	0	0	0
148	01/24/2009 05:32:05.65	01/24/2009 05:33:32.59	0:01:26.94	1:08:14.78	0	0	0
149	01/24/2009 06:41:47.37	01/24/2009 06:45:20.66	0:03:33.29	0:40:15.08	1	0	0
150	01/24/2009 07:25:35.74	01/24/2009 07:31:50.16	0:06:14.42	3:14:43.05	1	1	0
151	01/24/2009 10:46:33.21	01/24/2009 10:49:30.56	0:02:57.36	0:22:55.60	1	0	0
152	01/24/2009 11:12:26.16	01/24/2009 11:14:25.56	0:01:59.40	0:49:35.60	0	0	0
153	01/24/2009 12:04:01.16	01/24/2009 12:05:17.67	0:01:16.51	1:42:54.08	0	0	0
154	01/24/2009 13:48:11.75	01/24/2009 13:54:20.38	0:06:08.62	1:15:16.44	1	1	0
155	01/24/2009 15:09:36.82	01/24/2009 15:11:45.49	0:02:08.67	1:04:38.90	0	0	0
156	01/24/2009 16:16:24.39	01/24/2009 16:19:02.04	0:02:37.65	1:42:30.69	0	0	0
157	01/24/2009 18:01:32.73	01/24/2009 18:03:04.31	0:01:31.58	0:28:08.38	0	0	0
158	01/24/2009 18:31:12.68	01/24/2009 18:34:50.61	0:03:37.93	1:44:29.21	1	0	0
159	01/24/2009 20:19:19.82	01/24/2009 20:21:16.90	0:01:57.08	3:03:58.92	1	0	0

#	Start Time	End Time	Duration	Repose	T	H	A
160	01/24/2009 23:25:15.83	01/24/2009 23:31:51.11	0:06:35.29	0:56:34.06	1	0	0
161	01/25/2009 00:28:25.17	01/25/2009 00:30:04.86	0:01:39.69	1:19:13.92	0	0	0
162	01/25/2009 01:49:18.78	01/25/2009 01:52:24.25	0:03:05.47	0:43:49.63	1	1	0
163	01/25/2009 02:36:13.88	01/25/2009 02:42:10.91	0:05:57.03	0:18:37.42	1	0	0
164	01/25/2009 03:00:48.33	01/25/2009 03:04:15.83	0:03:27.50	2:28:31.42	1	0	0
165	01/25/2009 05:41:35.03	01/25/2009 05:45:48.89	0:04:13.86	1:03:55.31	1	0	0
166	01/25/2009 06:49:44.20	01/25/2009 06:52:20.69	0:02:36.49	1:02:43.46	1	0	0
167	01/25/2009 07:55:04.15	01/25/2009 07:56:22.98	0:01:18.83	0:55:59.65	0	0	0
168	01/25/2009 08:52:22.62	01/25/2009 09:02:13.81	0:09:51.19	1:26:09.55	1	1	0
169	01/25/2009 10:28:23.37	01/25/2009 10:30:05.37	0:01:42.01	0:47:35.41	0	0	0
170	01/25/2009 11:17:40.78	01/25/2009 11:20:35.82	0:02:55.04	0:51:55.91	1	0	0
171	01/25/2009 12:12:31.73	01/25/2009 12:15:43.00	0:03:11.27	2:33:13.86	1	0	0
172	01/25/2009 14:48:56.86	01/25/2009 14:53:52.46	0:04:55.60	4:58:14.07	1	0	0
173	01/25/2009 19:52:06.53	01/25/2009 19:53:45.06	0:01:38.53	0:49:21.59	0	0	0
174	01/25/2009 20:43:06.65	01/25/2009 20:47:15.88	0:04:09.23	2:07:41.59	1	0	0
175	01/25/2009 22:54:57.47	01/25/2009 22:58:33.08	0:03:35.61	1:31:18.83	1	1	0
176	01/26/2009 00:29:51.91	01/26/2009 00:35:06.05	0:05:14.14	0:31:21.53	1	1	0
177	01/26/2009 01:06:27.59	01/26/2009 01:10:19.43	0:03:51.84	0:45:48.93	1	0	0
178	01/26/2009 01:56:08.35	01/26/2009 01:58:47.16	0:02:38.81	0:20:24.84	1	1	0
179	01/26/2009 02:19:12.00	01/26/2009 02:22:01.25	0:02:49.24	0:10:16.02	1	0	0
180	01/26/2009 02:32:17.26	01/26/2009 02:40:21.81	0:08:04.54	0:30:19.51	1	0	0
181	01/26/2009 03:10:41.31	01/26/2009 03:17:20.08	0:06:38.76	2:31:08.01	0	0	0
182	01/26/2009 05:54:36.66	01/26/2009 05:58:04.16	0:03:27.50	1:51:47.13	1	1	0
183	01/26/2009 07:49:51.29	01/26/2009 07:51:40.26	0:01:48.96	0:50:22.28	1	0	0
184	01/26/2009 08:42:02.54	01/26/2009 08:48:38.98	0:06:36.45	1:55:03.28	1	0	0
185	01/26/2009 10:43:42.26	01/26/2009 10:45:52.09	0:02:09.83	1:21:09.48	1	0	0
186	01/26/2009 12:07:01.57	01/26/2009 12:08:23.88	0:01:22.30	7:04:37.32	0	0	0
187	01/26/2009 19:13:01.20	01/26/2009 19:16:57.68	0:03:56.48	0:59:47.27	1	0	0
188	01/26/2009 20:16:44.95	01/26/2009 20:19:26.08	0:02:41.13	1:56:07.88	1	0	0
189	01/26/2009 22:15:33.96	01/26/2009 22:16:59.74	0:01:25.78	2:37:27.31	0	0	0
190	01/27/2009 00:54:27.05	01/27/2009 01:02:16.53	0:07:49.47	0:56:15.02	1	1	0
191	01/27/2009 01:58:31.55	01/27/2009 02:05:26.54	0:06:54.99	1:32:01.18	1	1	1
192	01/27/2009 03:37:27.72	01/27/2009 03:41:12.61	0:03:44.88	0:32:07.74	1	1	0
193	01/27/2009 04:13:20.34	01/27/2009 04:14:28.73	0:01:08.39	1:31:26.24	1	0	0
194	01/27/2009 05:45:54.97	01/27/2009 05:48:12.92	0:02:17.94	0:17:07.16	1	1	0
195	01/27/2009 06:05:20.07	01/27/2009 06:12:54.48	0:07:34.40	0:40:13.70	1	1	0
196	01/27/2009 06:53:08.18	01/27/2009 06:56:53.06	0:03:44.88	2:17:29.54	1	0	0
197	01/27/2009 09:14:22.60	01/27/2009 09:23:23.95	0:09:01.34	1:28:16.66	1	1	1
198	01/27/2009 10:51:40.61	01/27/2009 10:53:36.53	0:01:55.92	3:40:43.65	1	0	0
199	01/27/2009 14:34:20.18	01/27/2009 14:41:45.31	0:07:25.13	0:33:23.65	1	1	0
200	01/27/2009 15:15:08.96	01/27/2009 15:17:35.02	0:02:26.06	3:58:18.09	1	0	0

#	Start Time	End Time	Duration	Repose	T	H	A
201	01/27/2009 19:15:53.11	01/27/2009 19:31:05.40	0:15:12.29	2:09:54.33	1	1	0
202	01/27/2009 21:40:59.73	01/27/2009 21:44:55.05	0:03:55.32	0:09:32.43	1	1	0
203	01/27/2009 21:54:27.48	01/27/2009 21:57:56.14	0:03:28.66	2:56:19.69	1	0	0
204	01/28/2009 00:54:16.60	01/28/2009 00:59:55.09	0:05:38.49	1:42:16.73	1	0	0
205	01/28/2009 02:42:11.82	01/28/2009 02:46:34.96	0:04:23.14	1:15:03.07	1	0	0
206	01/28/2009 04:01:38.03	01/28/2009 04:05:14.80	0:03:36.77	2:04:20.74	1	0	0
207	01/28/2009 06:09:35.54	01/28/2009 06:13:19.27	0:03:43.72	0:37:19.73	1	1	1
208	01/28/2009 06:50:38.99	01/28/2009 06:52:08.25	0:01:29.26	0:38:42.40	0	0	0
209	01/28/2009 07:30:50.65	01/28/2009 07:32:58.16	0:02:07.51	1:06:44.68	1	0	0
210	01/28/2009 08:39:44.23	01/28/2009 08:43:31.44	0:03:47.20	1:28:02.28	1	0	0
211	01/28/2009 10:11:33.72	01/28/2009 10:12:28.20	0:00:54.48	1:59:16.01	0	0	0
212	01/28/2009 12:11:44.21	01/28/2009 12:17:20.37	0:05:36.17	1:32:30.43	0	0	0
213	01/28/2009 13:49:50.80	01/28/2009 13:59:50.11	0:09:59.30	0:24:22.95	1	1	0
214	01/28/2009 14:24:13.06	01/28/2009 14:25:28.41	0:01:15.35	1:26:27.22	0	0	0
215	01/31/2009 00:34:35.93	01/31/2009 00:35:55.04	0:01:19.11	1:14:34.74	0	0	0
216	01/31/2009 01:50:29.79	01/31/2009 01:52:28.02	0:01:58.24	3:57:33.15	1	0	0
217	01/31/2009 05:50:01.18	01/31/2009 05:51:15.36	0:01:14.19	7:59:20.13	0	0	0
218	01/31/2009 13:50:35.49	01/31/2009 13:51:53.16	0:01:17.67	2:39:05.05	0	0	0
219	01/31/2009 16:30:58.21	01/31/2009 16:34:51.21	0:03:53.00	2:34:03.01	1	0	0
220	01/31/2009 19:08:54.21	01/31/2009 19:10:58.25	0:02:04.03	1:03:41.69	1	1	0
221	01/31/2009 20:14:39.94	01/31/2009 20:16:41.65	0:02:01.72	5:07:25.87	1	0	0
222	02/01/2009 01:24:07.52	02/01/2009 01:28:50.37	0:04:42.84	2:29:11.57	1	0	0
223	02/01/2009 03:58:01.93	02/01/2009 04:00:21.04	0:02:19.10	2:37:14.17	1	1	1
224	02/01/2009 06:37:35.20	02/01/2009 06:39:17.21	0:01:42.01	0:12:06.19	1	0	0
225	02/01/2009 06:51:23.40	02/01/2009 06:52:28.32	0:01:04.91	1:44:32.08	0	0	0
226	02/01/2009 08:37:00.40	02/01/2009 08:41:28.17	0:04:27.77	1:19:00.73	1	1	1
227	02/01/2009 10:00:28.90	02/01/2009 10:04:46.24	0:04:17.34	1:56:18.18	1	0	0
228	02/01/2009 12:01:04.42	02/01/2009 12:03:43.23	0:02:38.81	0:08:42.40	1	0	0
229	02/01/2009 12:12:25.63	02/01/2009 12:13:51.41	0:01:25.78	1:33:20.32	0	0	0
230	02/01/2009 13:47:11.73	02/01/2009 13:49:56.34	0:02:44.61	2:18:55.28	1	1	1
231	02/01/2009 16:08:51.62	02/01/2009 16:10:01.17	0:01:09.55	0:30:02.31	0	0	0
232	02/01/2009 16:40:03.48	02/01/2009 16:45:17.62	0:05:14.14	1:27:15.72	1	1	0
233	02/01/2009 18:12:33.34	02/01/2009 18:21:33.53	0:09:00.19	0:13:17.52	1	1	0
234	02/01/2009 18:34:51.05	02/01/2009 18:36:11.03	0:01:19.98	0:47:51.73	0	0	0
235	02/01/2009 19:24:02.76	02/01/2009 19:25:48.25	0:01:45.49	0:19:01.54	1	0	0
236	02/01/2009 19:44:49.79	02/01/2009 19:46:28.32	0:01:38.53	2:24:14.28	1	0	0
237	02/01/2009 22:10:42.60	02/01/2009 22:20:27.99	0:09:45.39	1:11:39.90	1	1	1
238	02/01/2009 23:32:07.89	02/01/2009 23:33:17.44	0:01:09.55	0:54:13.37	0	0	0
239	02/02/2009 00:27:30.81	02/02/2009 00:33:17.41	0:05:46.60	2:17:45.73	1	1	1
240	02/02/2009 02:51:04.63	02/02/2009 03:11:48.45	0:20:43.82	0:33:49.16	1	1	1
241	02/02/2009 03:45:37.61	02/02/2009 03:49:46.84	0:04:09.23	0:45:12.53	1	0	0

#	Start Time	End Time	Duration	Repose	T	H	A
242	02/02/2009 04:34:59.37	02/02/2009 04:44:44.77	0:09:45.39	3:17:56.35	1	1	0
243	02/02/2009 08:02:41.11	02/02/2009 08:12:53.17	0:10:12.06	1:17:12.67	1	1	1
244	02/02/2009 09:30:05.84	02/02/2009 09:33:47.25	0:03:41.41	2:49:03.85	1	1	0
245	02/02/2009 12:22:51.10	02/02/2009 12:31:02.60	0:08:11.50	0:08:15.89	1	1	0
246	02/02/2009 12:39:18.49	02/02/2009 12:51:58.92	0:12:40.43	0:35:16.77	1	1	0
247	02/02/2009 13:27:15.69	02/02/2009 13:28:49.59	0:01:33.89	0:29:02.22	0	0	0
248	03/14/2009 01:00:50.71	03/14/2009 01:03:12.13	0:02:21.42	0:38:09.18	1	0	0
249	03/14/2009 01:41:21.31	03/14/2009 01:42:40.14	0:01:18.83	1:57:36.31	0	0	0
250	03/14/2009 03:54:10.02	03/14/2009 03:55:20.73	0:01:10.71	1:18:02.98	0	0	0
251	03/14/2009 05:13:23.71	03/14/2009 05:19:02.19	0:05:38.49	1:16:07.71	1	0	0
252	03/14/2009 06:35:09.90	03/14/2009 06:39:31.88	0:04:21.98	0:53:35.59	1	1	0
253	03/14/2009 07:33:07.47	03/14/2009 07:34:54.12	0:01:46.65	0:12:43.91	0	0	0
254	03/14/2009 07:47:38.03	03/14/2009 07:49:10.77	0:01:32.74	1:04:48.50	0	0	0
255	03/14/2009 08:53:59.27	03/14/2009 08:55:33.17	0:01:33.89	0:26:04.55	1	0	0
256	03/14/2009 09:21:37.72	03/14/2009 09:23:39.43	0:02:01.72	2:18:15.36	0	0	0
257	03/14/2009 11:41:54.79	03/14/2009 11:44:11.58	0:02:16.79	1:50:42.85	0	0	0
258	03/14/2009 13:34:54.42	03/14/2009 13:42:12.60	0:07:18.18	1:42:24.27	1	1	0
259	03/14/2009 15:24:36.87	03/14/2009 15:29:59.13	0:05:22.26	0:53:22.62	1	1	0
260	03/14/2009 16:23:21.75	03/14/2009 16:26:31.86	0:03:10.11	0:17:31.42	1	1	0
261	03/14/2009 16:44:03.28	03/14/2009 16:45:00.08	0:00:56.80	0:28:12.76	0	0	0
262	03/14/2009 17:13:12.84	03/14/2009 17:18:53.65	0:05:40.80	0:53:49.19	0	0	0
263	03/14/2009 18:12:42.84	03/14/2009 18:15:56.43	0:03:13.59	1:11:03.79	1	1	0
264	03/14/2009 19:27:00.21	03/14/2009 19:31:01.32	0:04:01.11	1:14:10.16	0	0	0
265	03/14/2009 20:45:11.48	03/14/2009 20:48:45.93	0:03:34.45	2:30:32.96	1	0	0
266	03/14/2009 23:19:18.89	03/14/2009 23:22:38.27	0:03:19.38	1:06:21.97	1	0	0
267	03/15/2009 00:29:00.24	03/15/2009 00:29:54.73	0:00:54.48	2:19:28.73	0	0	0
268	03/15/2009 02:49:23.46	03/15/2009 02:53:22.25	0:03:58.79	1:42:55.71	1	1	0
269	03/15/2009 04:36:17.96	03/15/2009 04:37:13.60	0:00:55.64	1:54:07.25	0	0	0
270	03/15/2009 06:31:20.85	03/15/2009 06:38:27.44	0:07:06.58	0:21:57.76	1	1	0
271	03/15/2009 07:00:25.19	03/15/2009 07:07:28.30	0:07:03.11	1:12:52.99	1	1	0
272	03/15/2009 08:20:21.29	03/15/2009 08:24:53.70	0:04:32.41	0:34:46.53	1	1	0
273	03/15/2009 08:59:40.23	03/15/2009 09:01:52.38	0:02:12.15	0:56:17.57	1	0	0
274	03/15/2009 09:58:09.95	03/15/2009 10:00:58.03	0:02:48.08	0:37:22.50	1	0	0
275	03/15/2009 10:38:20.53	03/15/2009 10:41:52.67	0:03:32.13	1:36:03.56	1	0	0
276	03/15/2009 12:17:56.22	03/15/2009 12:21:37.63	0:03:41.41	0:25:13.50	1	0	0
277	03/15/2009 12:46:51.13	03/15/2009 12:50:12.83	0:03:21.70	5:58:04.60	1	0	0
278	03/15/2009 18:48:17.43	03/15/2009 18:52:57.96	0:04:40.53	0:20:15.36	1	1	0
279	03/15/2009 19:13:14.80	03/15/2009 19:21:08.91	0:07:54.11	2:37:00.73	1	0	0
280	03/15/2009 21:58:10.02	03/15/2009 22:04:40.67	0:06:30.65	1:46:21.32	1	1	1
281	03/15/2009 23:51:01.99	03/15/2009 23:53:40.31	0:02:38.32	1:32:01.63	1	1	1
282	03/16/2009 01:25:41.94	03/16/2009 01:27:49.45	0:02:07.51	1:41:12.73	0	0	0

#	Start Time	End Time	Duration	Repose	T	H	A
283	03/16/2009 03:09:02.18	03/16/2009 03:12:01.86	0:02:59.68	1:12:21.60	1	0	0
284	03/16/2009 04:24:23.45	03/16/2009 04:26:56.47	0:02:33.01	0:20:08.51	1	1	0
285	03/16/2009 04:47:04.98	03/16/2009 04:50:22.04	0:03:17.06	1:48:12.40	1	0	0
286	03/16/2009 06:38:34.44	03/16/2009 06:40:36.16	0:02:01.72	5:45:51.36	0	0	0
287	03/16/2009 12:26:27.51	03/16/2009 12:31:39.34	0:05:11.82	0:29:34.08	1	1	1
288	03/16/2009 13:01:13.42	03/16/2009 13:01:55.15	0:00:41.73	0:13:21.77	1	1	0
289	03/16/2009 13:15:16.92	03/16/2009 13:17:33.71	0:02:16.79	1:00:03.88	1	1	0
290	03/16/2009 14:17:37.58	03/16/2009 14:20:23.35	0:02:45.77	0:40:56.51	0	0	0
291	03/16/2009 15:01:19.85	03/16/2009 15:03:36.64	0:02:16.79	2:05:25.19	0	0	0
292	03/16/2009 17:09:01.83	03/16/2009 17:10:28.77	0:01:26.94	1:12:41.43	0	0	0
293	03/16/2009 18:23:10.20	03/16/2009 18:28:03.48	0:04:53.28	0:53:03.99	1	0	0
294	03/16/2009 19:21:07.46	03/16/2009 19:26:49.43	0:05:41.96	0:17:16.06	1	0	0
295	03/16/2009 19:44:05.49	03/16/2009 19:45:02.29	0:00:56.80	0:13:44.89	0	0	0
296	03/16/2009 19:58:47.18	03/16/2009 20:01:59.61	0:03:12.43	2:12:12.32	0	0	0
297	03/16/2009 22:14:11.93	03/16/2009 22:15:24.96	0:01:13.03	0:34:22.40	0	0	0
298	03/16/2009 22:49:47.36	03/16/2009 22:52:23.85	0:02:36.49	2:11:33.60	0	0	0
299	03/17/2009 01:03:57.45	03/17/2009 01:09:22.03	0:05:24.57	1:17:48.83	1	1	1
300	03/17/2009 02:27:10.85	03/17/2009 02:38:17.39	0:11:06.54	1:40:11.08	1	1	1
301	03/17/2009 04:18:28.47	03/17/2009 04:22:12.19	0:03:43.72	3:15:35.39	1	1	1
302	03/17/2009 07:37:47.58	03/17/2009 07:39:35.39	0:01:47.81	1:19:33.42	0	0	0
303	03/17/2009 08:59:08.81	03/17/2009 09:04:10.20	0:05:01.39	1:00:16.45	1	0	0
304	03/17/2009 10:04:26.65	03/17/2009 10:09:35.00	0:05:08.35	0:09:43.06	1	1	1
305	03/17/2009 10:19:18.06	03/17/2009 10:20:19.50	0:01:01.44	0:35:37.18	0	0	0
306	03/17/2009 10:55:56.67	03/17/2009 11:00:34.88	0:04:38.21	2:23:33.63	1	0	0
307	03/17/2009 13:24:08.51	03/17/2009 13:28:13.10	0:04:04.59	1:05:53.35	1	1	1
308	03/17/2009 14:34:06.45	03/17/2009 14:36:11.65	0:02:05.19	1:29:30.59	0	0	0
309	03/17/2009 16:05:42.24	03/17/2009 16:14:09.97	0:08:27.73	1:27:44.86	1	0	0
310	03/17/2009 17:41:54.82	03/17/2009 17:45:14.20	0:03:19.38	4:10:30.76	1	0	0
311	03/17/2009 21:55:44.96	03/17/2009 21:58:34.20	0:02:49.24	1:13:40.49	1	0	0
312	03/17/2009 23:12:14.69	03/17/2009 23:17:48.54	0:05:33.85	0:45:33.76	1	1	1
313	03/18/2009 00:03:22.31	03/18/2009 00:04:17.51	0:00:55.20	2:54:01.50	0	0	0
314	03/18/2009 02:58:19.01	03/18/2009 03:09:24.39	0:11:05.38	1:02:12.70	1	1	0
315	03/18/2009 04:11:37.09	03/18/2009 04:14:01.99	0:02:24.90	1:56:52.91	0	0	0
316	03/18/2009 06:10:54.90	03/18/2009 06:13:19.80	0:02:24.90	4:53:34.29	1	0	0
317	03/18/2009 11:06:54.09	03/18/2009 11:14:26.18	0:07:32.09	0:24:46.11	1	0	0
318	03/18/2009 11:39:12.29	03/18/2009 11:40:27.64	0:01:15.35	1:09:29.96	0	0	0
319	03/18/2009 12:49:57.60	03/18/2009 12:53:40.17	0:03:42.57	2:58:14.02	1	0	0
320	03/18/2009 15:51:54.18	03/18/2009 15:55:28.64	0:03:34.45	0:08:25.68	1	0	0
321	03/18/2009 16:03:54.31	03/18/2009 16:07:53.11	0:03:58.79	1:42:47.40	1	0	0
322	03/18/2009 17:50:40.50	03/18/2009 17:54:32.34	0:03:51.84	1:31:58.26	1	1	0
323	03/18/2009 19:26:30.61	03/18/2009 19:32:10.25	0:05:39.64	1:10:12.99	1	1	0

#	Start Time	End Time	Duration	Repose	T	H	A
324	03/18/2009 20:42:23.24	03/18/2009 20:43:15.40	0:00:52.16	0:44:10.41	0	0	0
325	03/18/2009 21:27:25.81	03/18/2009 21:29:41.44	0:02:15.63	1:10:59.33	1	0	0
326	03/18/2009 22:40:40.77	03/18/2009 22:49:01.54	0:08:20.77	2:22:12.71	1	0	0
327	03/19/2009 01:11:14.25	03/19/2009 01:16:06.37	0:04:52.12	0:00:03.35	1	1	0
328	03/19/2009 01:16:09.72	03/19/2009 01:19:18.67	0:03:08.95	0:46:07.11	1	0	0
329	03/19/2009 02:05:25.78	03/19/2009 02:07:19.38	0:01:53.60	0:23:23.42	1	0	0
330	03/19/2009 02:30:42.80	03/19/2009 02:33:36.68	0:02:53.88	1:48:59.35	1	0	0
331	03/19/2009 04:22:36.03	03/19/2009 04:26:20.92	0:03:44.88	1:02:21.38	1	0	0
332	03/19/2009 05:28:42.30	03/19/2009 05:30:02.29	0:01:19.98	0:22:20.14	0	0	0
333	03/19/2009 05:52:22.42	03/19/2009 05:56:07.31	0:03:44.88	1:33:00.16	1	0	0
334	03/19/2009 07:29:07.47	03/19/2009 07:33:42.20	0:04:34.73	1:25:19.12	1	0	0
335	03/19/2009 08:59:01.31	03/19/2009 09:08:57.14	0:09:55.83	2:10:39.49	1	1	1
336	03/19/2009 11:19:36.62	03/19/2009 11:24:35.70	0:04:59.07	0:30:27.14	1	1	1
337	03/19/2009 11:55:02.83	03/19/2009 11:57:30.05	0:02:27.22	2:33:03.40	0	0	0
338	03/19/2009 14:30:33.45	03/19/2009 14:31:25.62	0:00:52.16	0:59:41.47	0	0	0
339	03/19/2009 15:31:07.08	03/19/2009 15:35:00.08	0:03:53.00	1:38:15.51	1	1	0
340	03/19/2009 17:13:15.59	03/19/2009 17:15:21.94	0:02:06.35	1:09:41.01	0	0	0
341	03/19/2009 18:25:02.95	03/19/2009 18:26:02.07	0:00:59.12	0:48:22.19	1	0	0
342	03/19/2009 19:14:24.26	03/19/2009 19:16:01.63	0:01:37.37	3:58:05.19	0	0	0
343	03/19/2009 23:14:06.82	03/19/2009 23:16:01.58	0:01:54.76	1:43:11.65	0	0	0
344	03/20/2009 00:59:15.87	03/20/2009 01:08:06.78	0:08:50.91	0:39:03.02	1	0	0
345	03/20/2009 01:47:09.80	03/20/2009 01:52:28.58	0:05:18.78	0:12:33.94	1	0	0
346	03/20/2009 02:05:02.52	03/20/2009 02:06:07.44	0:01:04.91	0:50:48.21	0	0	0
347	03/20/2009 02:56:55.65	03/20/2009 02:58:09.84	0:01:14.19	1:41:02.72	0	0	0
348	03/20/2009 04:39:12.56	03/20/2009 04:41:05.00	0:01:52.44	1:27:49.49	0	0	0
349	03/20/2009 06:08:54.50	03/20/2009 06:10:11.01	0:01:16.51	3:00:39.54	0	0	0
350	03/20/2009 09:10:50.54	03/20/2009 09:11:55.46	0:01:04.91	1:52:21.25	0	0	0
351	03/20/2009 11:04:16.70	03/20/2009 11:08:36.36	0:04:19.66	3:16:02.34	1	1	0
352	03/20/2009 14:24:38.70	03/20/2009 14:26:42.74	0:02:04.03	0:24:36.31	0	0	0
353	03/20/2009 14:51:19.05	03/20/2009 14:53:26.56	0:02:07.51	1:33:32.45	0	0	0
354	03/20/2009 16:26:59.01	03/20/2009 16:30:43.89	0:03:44.88	1:43:34.77	1	0	0
355	03/20/2009 18:14:18.66	03/20/2009 18:26:46.34	0:12:27.68	0:49:25.05	1	1	0
356	03/20/2009 19:16:11.39	03/20/2009 19:17:01.24	0:00:49.85	0:29:02.57	0	0	0
357	03/20/2009 19:46:03.81	03/20/2009 19:51:15.63	0:05:11.82	1:42:03.41	1	1	0
358	03/20/2009 21:33:19.04	03/20/2009 21:42:37.78	0:09:18.73	1:17:34.82	1	1	0
359	03/20/2009 23:00:12.59	03/20/2009 23:05:51.08	0:05:38.49	0:58:07.74	1	0	0
360	03/21/2009 00:03:58.82	03/21/2009 00:09:22.51	0:05:23.69	1:46:51.51	0	0	0
361	03/21/2009 01:56:14.02	03/21/2009 01:58:16.90	0:02:02.87	1:07:46.39	0	0	0
362	03/21/2009 03:06:03.29	03/21/2009 03:07:46.46	0:01:43.17	2:21:56.39	0	0	0
363	03/21/2009 05:29:42.85	03/21/2009 05:33:04.55	0:03:21.70	2:16:02.37	1	1	0
364	03/21/2009 07:49:06.92	03/21/2009 07:54:08.31	0:05:01.39	1:59:48.22	1	0	0

#	Start Time	End Time	Duration	Repose	T	H	A
365	03/21/2009 09:53:56.53	03/21/2009 09:57:51.85	0:03:55.32	1:11:04.54	1	1	0
366	03/21/2009 11:08:58.12	03/21/2009 11:19:43.79	0:10:45.67	0:18:59.65	1	1	0
367	03/21/2009 11:38:43.44	03/21/2009 11:40:49.79	0:02:06.35	1:55:14.55	0	0	0
368	03/21/2009 13:36:04.34	03/21/2009 13:42:59.34	0:06:54.99	0:31:09.80	1	1	0
369	03/21/2009 14:14:09.13	03/21/2009 14:15:21.00	0:01:11.87	0:45:53.86	0	0	0
370	03/21/2009 15:01:14.86	03/21/2009 15:03:49.04	0:02:34.17	2:02:25.76	0	0	0
371	03/21/2009 17:06:14.79	03/21/2009 17:08:25.78	0:02:10.99	1:11:40.39	1	0	0
372	03/21/2009 18:20:06.17	03/21/2009 18:25:38.86	0:05:32.69	2:27:40.72	0	1	0
373	03/21/2009 20:53:19.58	03/21/2009 20:58:08.22	0:04:48.64	0:11:56.76	1	1	0
374	03/21/2009 21:10:04.98	03/21/2009 21:11:51.63	0:01:46.65	1:33:27.94	1	0	0
375	03/21/2009 22:45:19.57	03/21/2009 22:46:41.87	0:01:22.30	1:58:12.18	0	0	0
376	03/22/2009 00:44:54.05	03/22/2009 00:48:51.69	0:03:57.64	1:37:27.85	1	0	0
377	03/22/2009 02:26:19.54	03/22/2009 02:28:18.94	0:01:59.40	2:33:35.13	1	0	0
378	03/22/2009 05:01:54.06	03/22/2009 05:06:28.79	0:04:34.73	1:33:54.93	1	1	0
379	03/22/2009 06:40:23.72	03/22/2009 06:49:30.86	0:09:07.14	0:34:06.97	1	1	0
380	03/22/2009 07:23:37.84	03/22/2009 07:27:37.79	0:03:59.95	1:14:58.14	1	0	0
381	03/22/2009 08:42:37.92	03/22/2009 08:46:06.58	0:03:28.66	0:51:33.18	0	0	0
382	03/22/2009 09:37:39.76	03/22/2009 09:40:20.89	0:02:41.13	0:31:16.34	0	0	0
383	03/22/2009 10:11:37.23	03/22/2009 10:19:15.11	0:07:37.88	0:21:30.34	1	1	0
384	03/22/2009 10:40:45.45	03/22/2009 10:42:33.25	0:01:47.81	0:41:02.99	1	0	0
385	03/22/2009 11:23:36.25	03/22/2009 11:25:11.30	0:01:35.05	0:45:57.16	1	0	0
386	03/22/2009 12:11:08.46	03/22/2009 12:14:04.66	0:02:56.20	0:51:51.26	1	0	0
387	03/27/2009 00:39:49.20	03/27/2009 00:40:56.43	0:01:07.23	0:24:54.23	0	0	0
388	03/27/2009 01:05:50.66	03/27/2009 01:08:36.43	0:02:45.77	1:41:05.18	1	0	0
389	03/27/2009 02:49:41.61	03/27/2009 02:58:16.30	0:08:34.68	1:14:38.35	1	1	1
390	03/27/2009 04:12:54.64	03/27/2009 04:14:42.45	0:01:47.81	1:48:44.43	0	0	0
391	03/27/2009 06:03:26.88	03/27/2009 06:11:26.79	0:07:59.91	0:58:56.60	1	1	1
392	03/27/2009 07:10:23.39	03/27/2009 07:13:52.05	0:03:28.66	0:55:57.34	1	1	0

9 Appendix B: Traces and STFT of Catalogue Events

Included on companion DVD.

Files included:

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338-20090319T143033.tif	358-20090320T213319.tif	378-20090322T050154.tif
339-20090319T153107.tif	359-20090320T230012.tif	379-20090322T064023.tif
340-20090319T171315.tif	360-20090321T000358.tif	380-20090322T072337.tif
341-20090319T182502.tif	361-20090321T015614.tif	381-20090322T084237.tif
342-20090319T191424.tif	362-20090321T030603.tif	382-20090322T093739.tif
343-20090319T231406.tif	363-20090321T052942.tif	383-20090322T101137.tif
344-20090320T005915.tif	364-20090321T074906.tif	384-20090322T104045.tif
345-20090320T014709.tif	365-20090321T095356.tif	385-20090322T112336.tif
346-20090320T020502.tif	366-20090321T110858.tif	386-20090322T121108.tif
347-20090320T025655.tif	367-20090321T113843.tif	387-20090327T003949.tif
348-20090320T043912.tif	368-20090321T133604.tif	388-20090327T010550.tif
349-20090320T060854.tif	369-20090321T141409.tif	389-20090327T024941.tif
350-20090320T091050.tif	370-20090321T150114.tif	390-20090327T041254.tif
351-20090320T110416.tif	371-20090321T170614.tif	391-20090327T060326.tif
352-20090320T142438.tif	372-20090321T182006.tif	392-20090327T071023.tif
353-20090320T145119.tif	373-20090321T205319.tif	
354-20090320T162659.tif	374-20090321T211004.tif	
355-20090320T181418.tif	375-20090321T224519.tif	
356-20090320T191611.tif	376-20090322T004454.tif	

Figure 9.1: TIFF image files for each event in the catalog of events containing seismic trace for the duration of the event and STFT spectrograms for frequencies of 0-12 Hz.

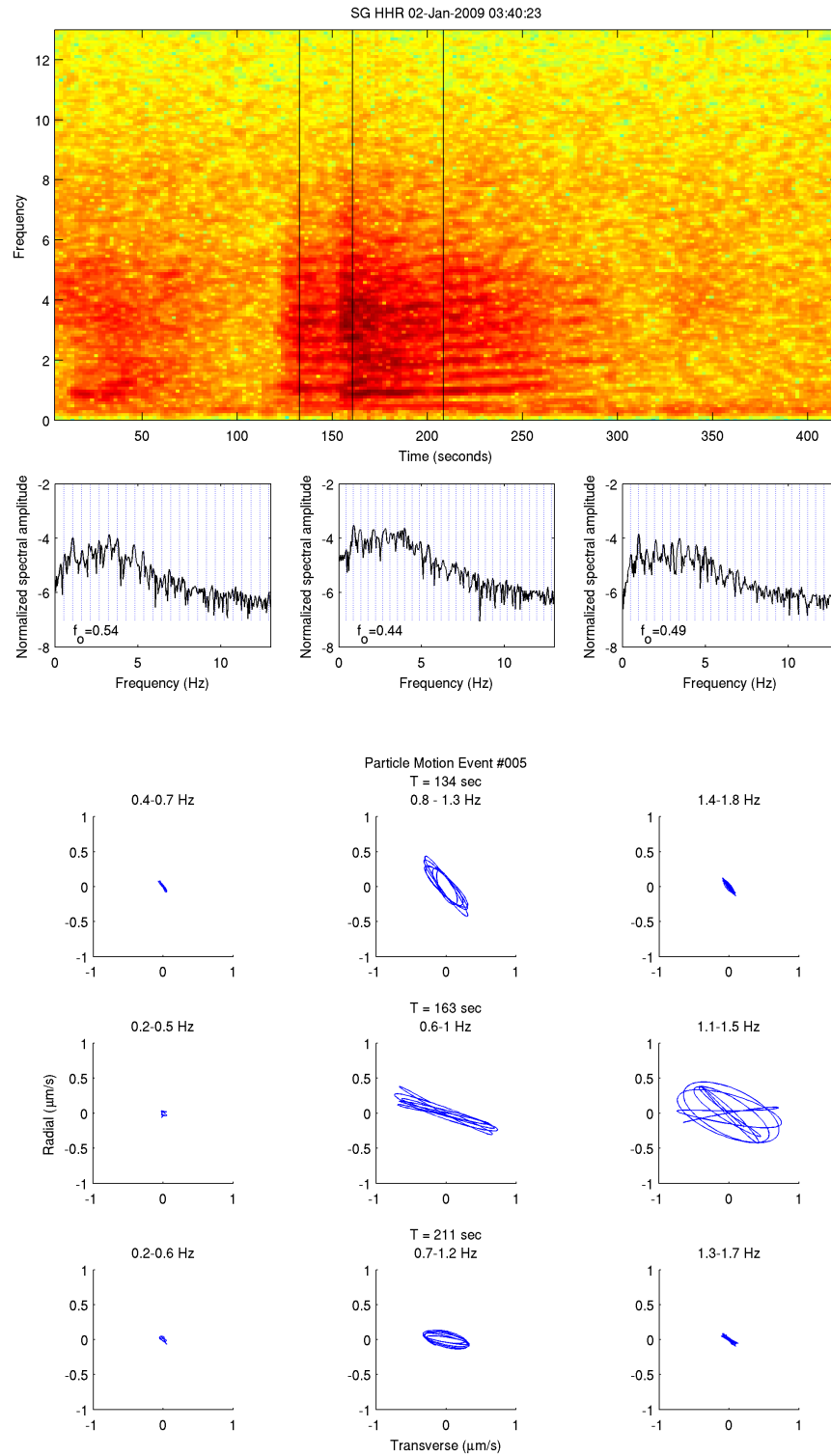
10 Appendix C: Representative Events

Table 10.1: Events representing common behavior over observation period duration

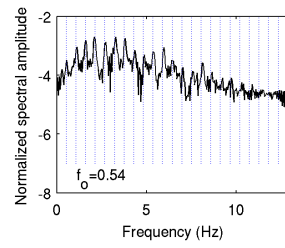
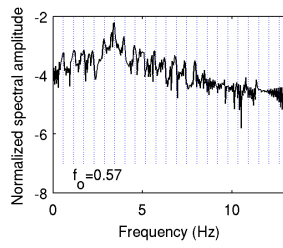
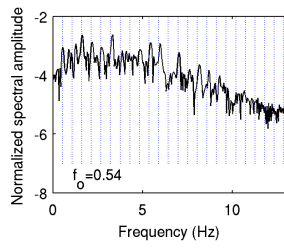
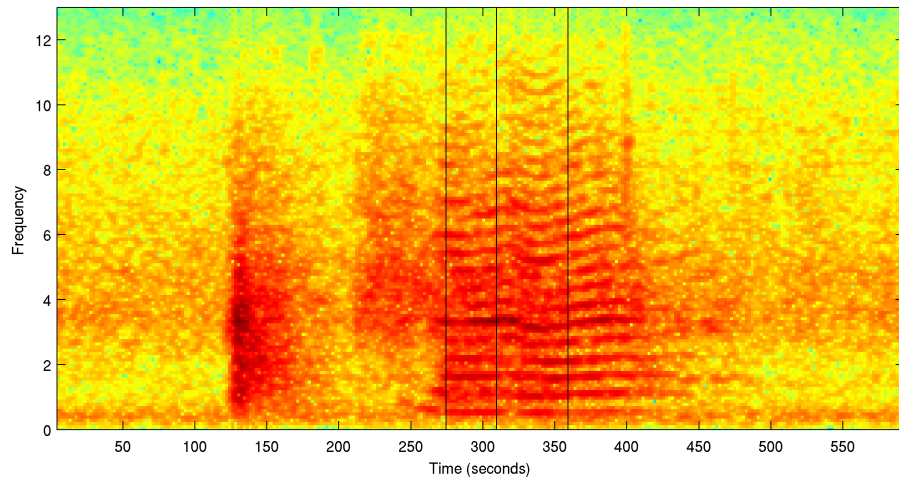
T = Tremor Events, H = Harmonic Tremor Events, A = Harmonic Tremor Events Coupled to the Acoustic

#	Start Time	End Time	Duration	Repose	T	H	A
5	01/02/2009 03:42:23.25	01/02/2009 03:45:25.24	0:03:01.99	1:19:18.34	1	1	1
66	01/06/2009 23:07:35.93	01/06/2009 23:13:34.13	0:05:58.19	0:28:22.20	1	1	1
88	01/08/2009 06:23:58.05	01/08/2009 06:29:44.65	0:05:46.60	0:51:57.57	1	1	1
117	01/22/2009 12:33:40.23	01/22/2009 12:40:39.86	0:06:59.63	1:04:02.75	1	1	1
133	01/23/2009 10:06:50.63	01/23/2009 10:12:36.07	0:05:45.44	0:30:10.28	1	1	1
223	02/01/2009 03:58:01.93	02/01/2009 04:00:21.04	0:02:19.10	2:37:14.17	1	1	1
243	02/02/2009 08:02:41.11	02/02/2009 08:12:53.17	0:10:12.06	1:17:12.67	1	1	1
299	03/17/2009 01:03:57.45	03/17/2009 01:09:22.03	0:05:24.57	1:17:48.83	1	1	1
300	03/17/2009 02:27:10.85	03/17/2009 02:38:17.39	0:11:06.54	1:40:11.08	1	1	1
335	03/19/2009 08:59:01.31	03/19/2009 09:08:57.14	0:09:55.83	2:10:39.49	1	1	1

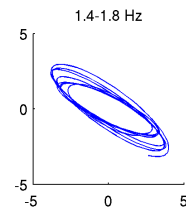
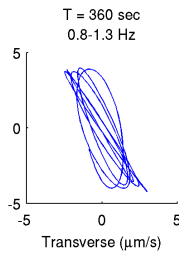
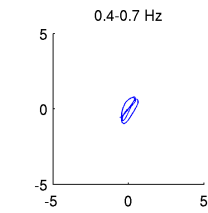
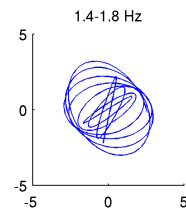
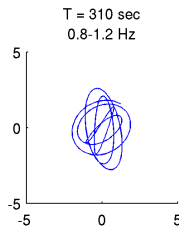
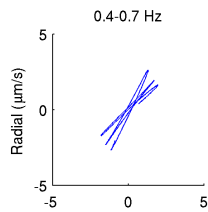
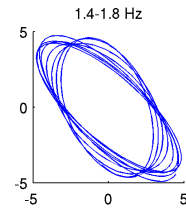
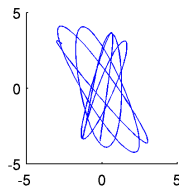
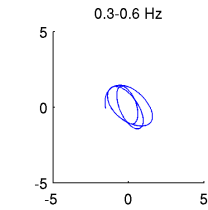
11 Appendix D: STFT and Particle Motion



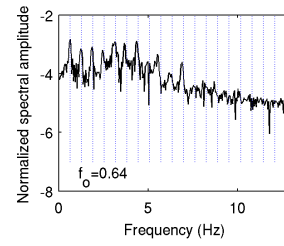
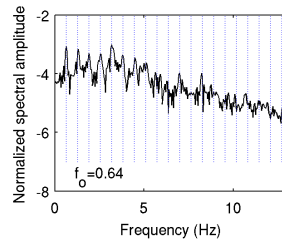
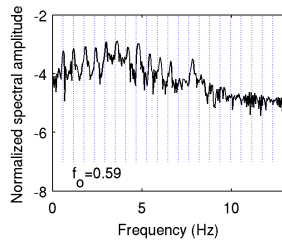
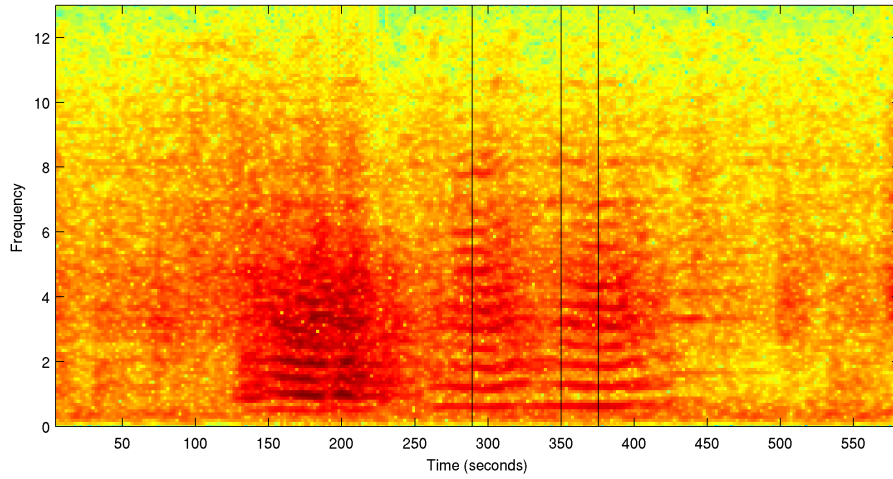
SG HHR 06-Jan-2009 23:05:35



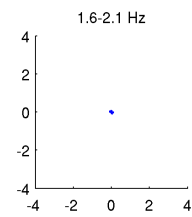
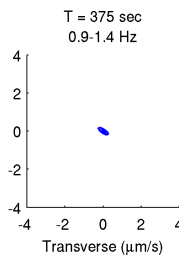
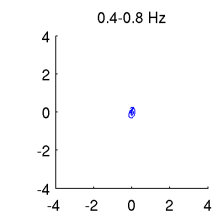
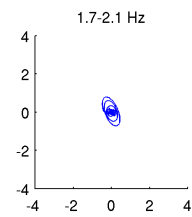
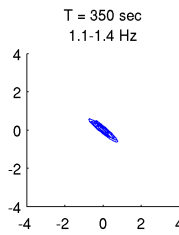
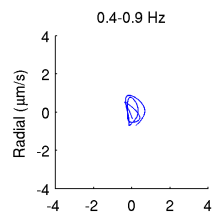
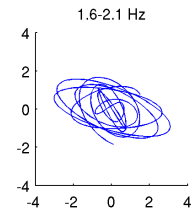
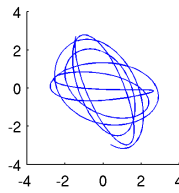
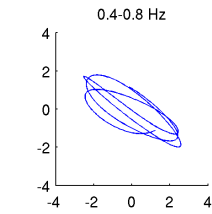
Particle Motion Event #066
T = 275 sec
0.8 - 1.2 Hz



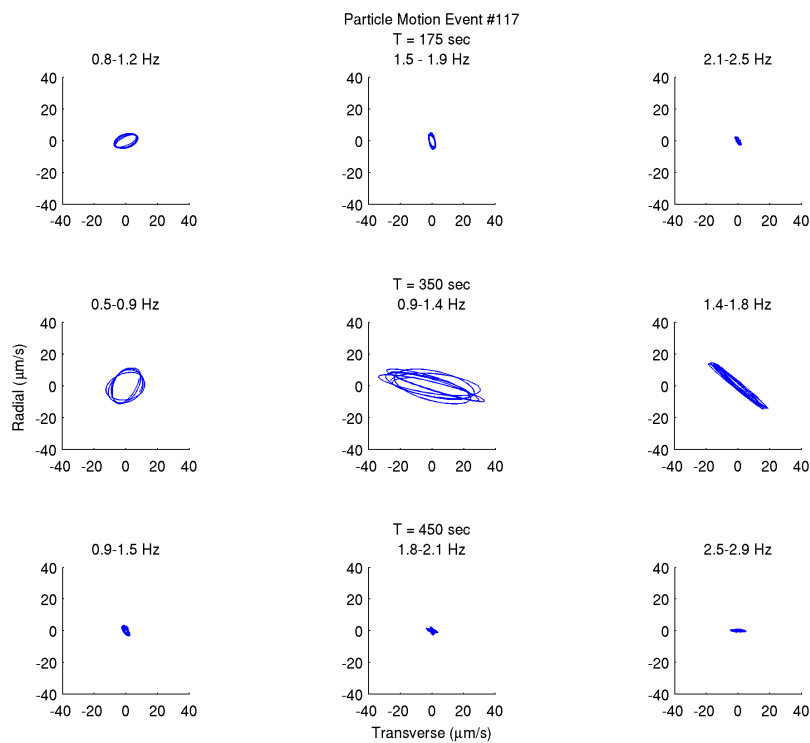
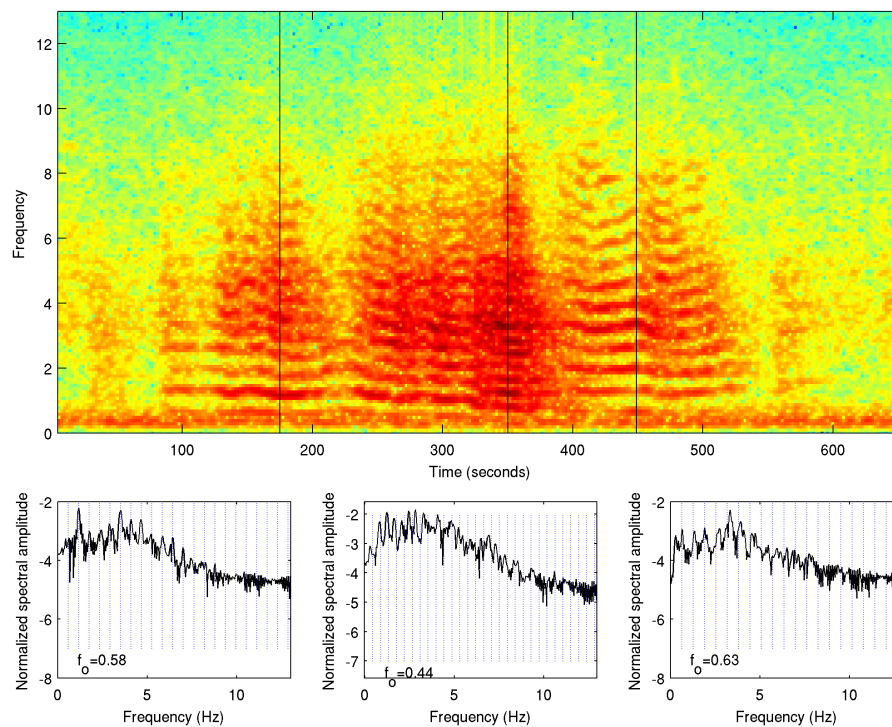
SG HHR 08-Jan-2009 06:21:58

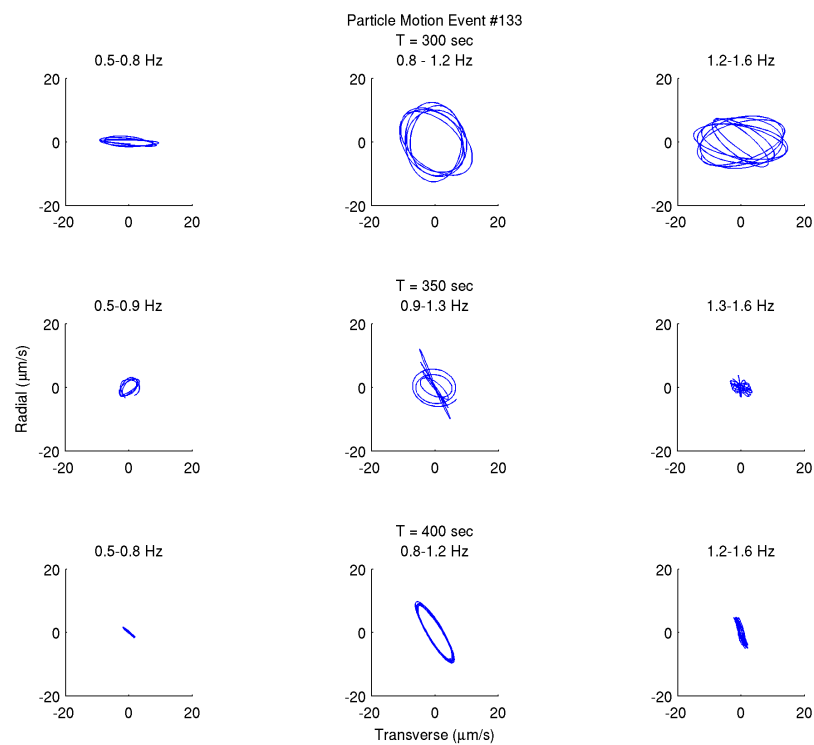
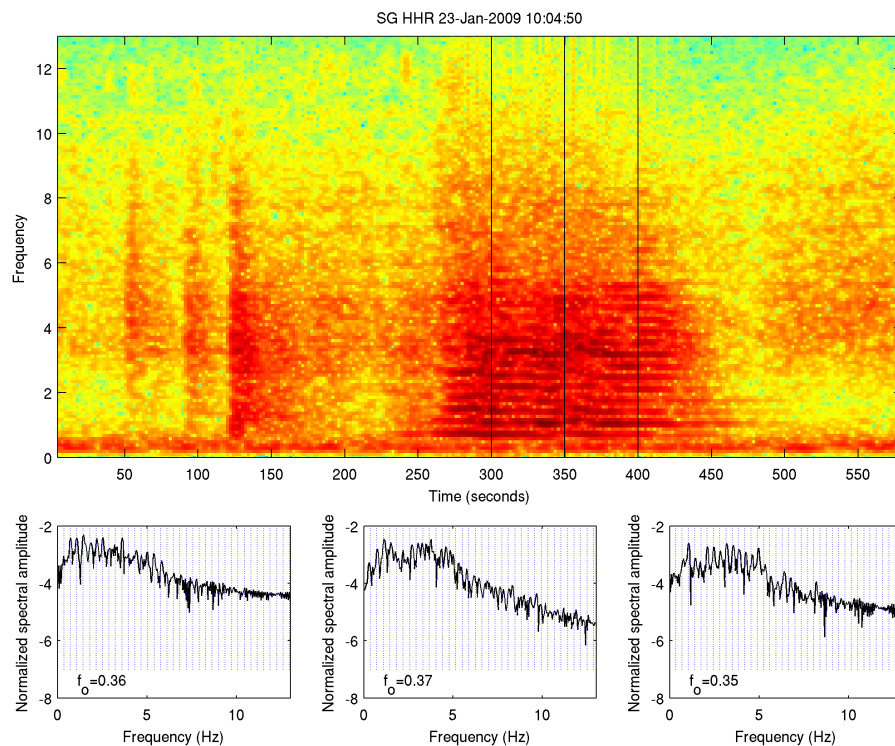


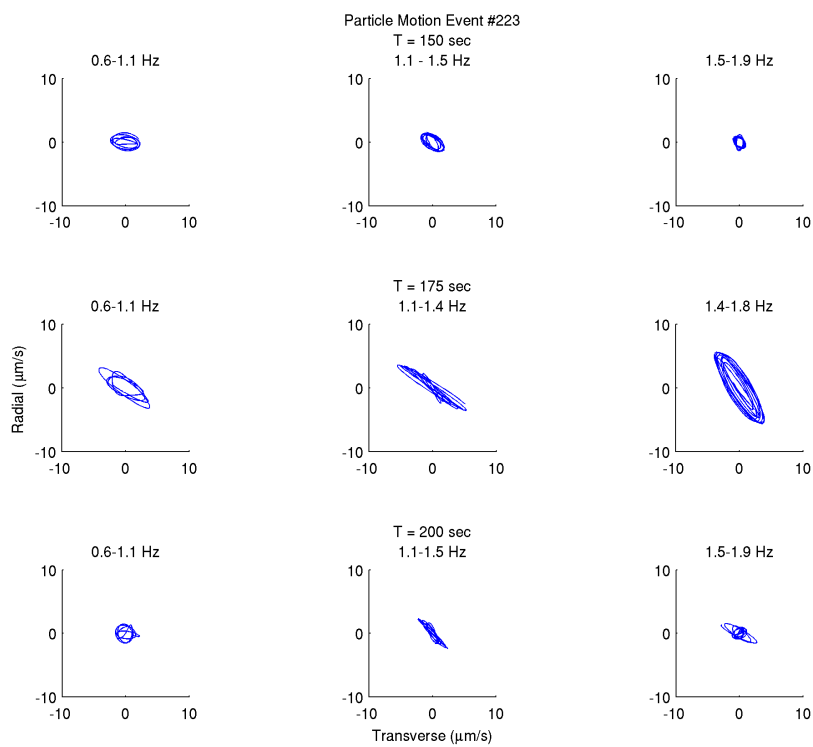
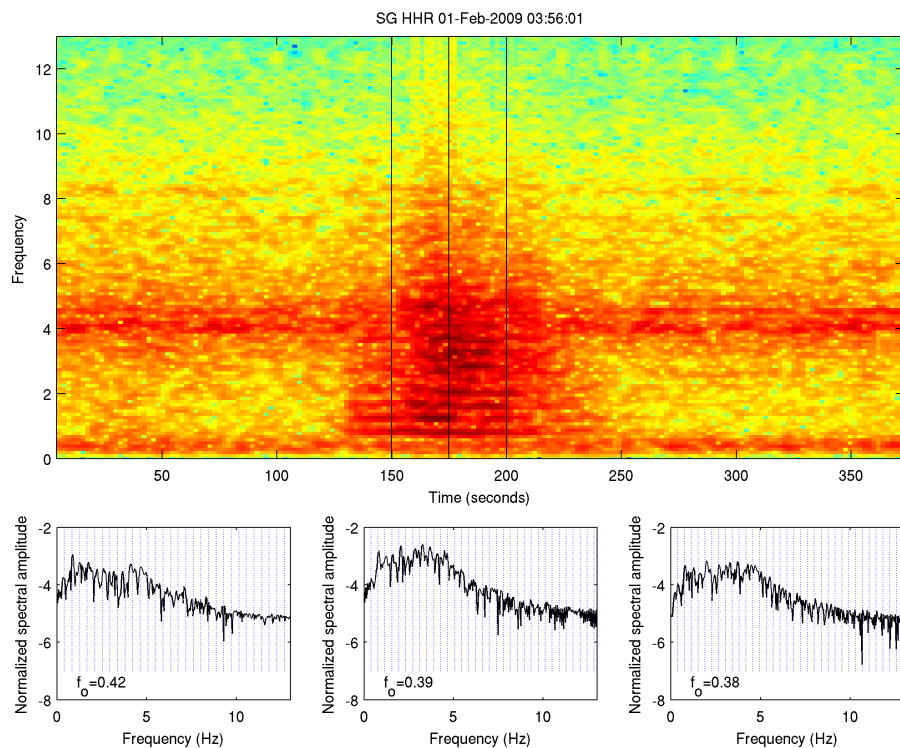
Particle Motion Event #088
T = 290 sec
0.9 - 1.4 Hz

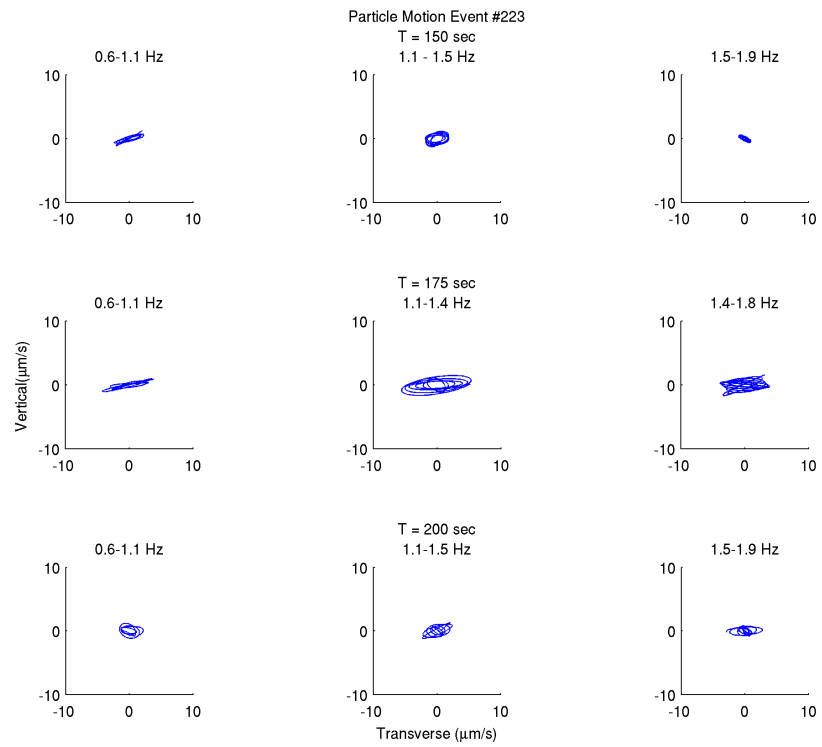
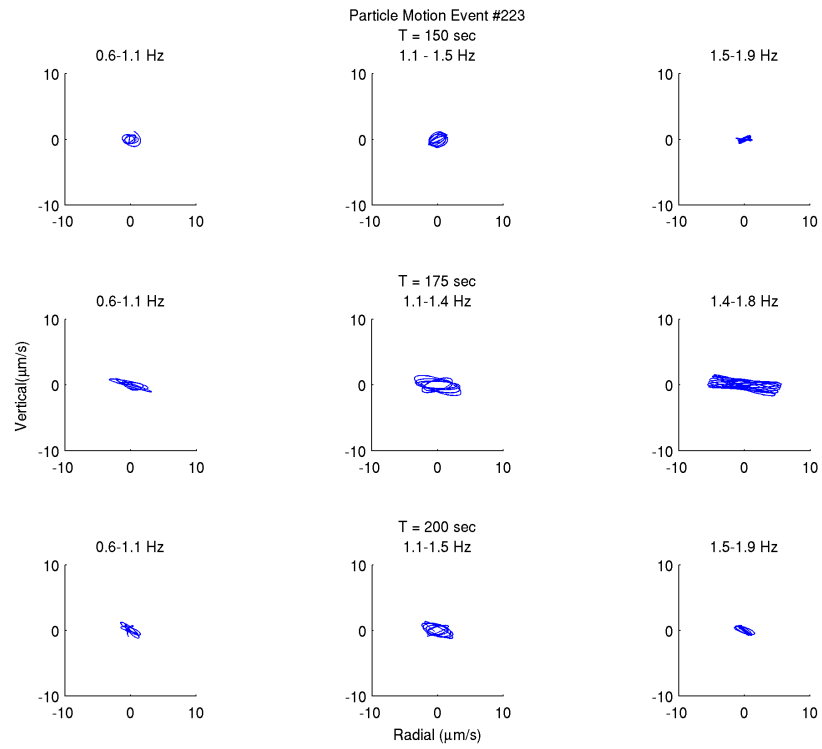


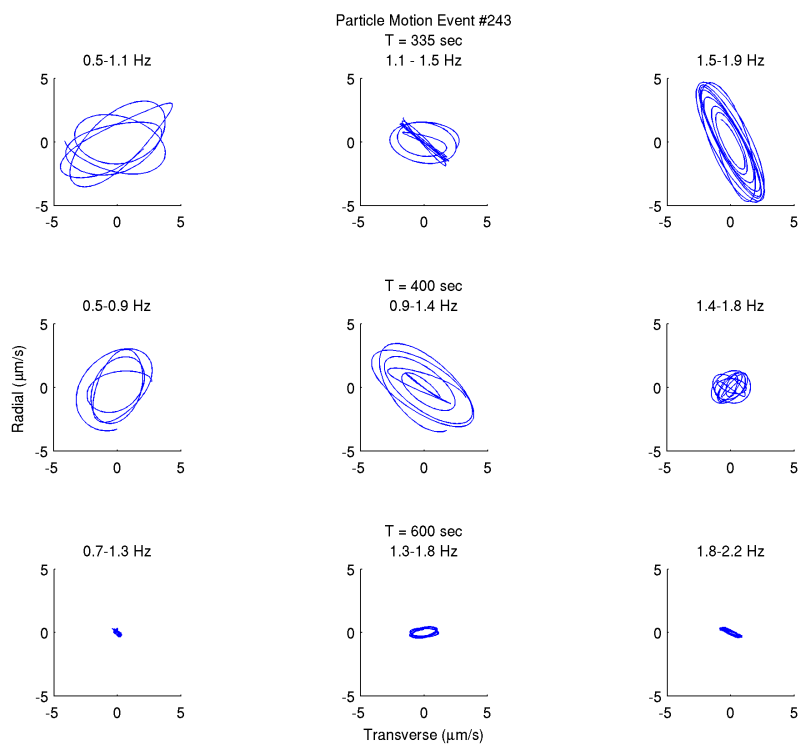
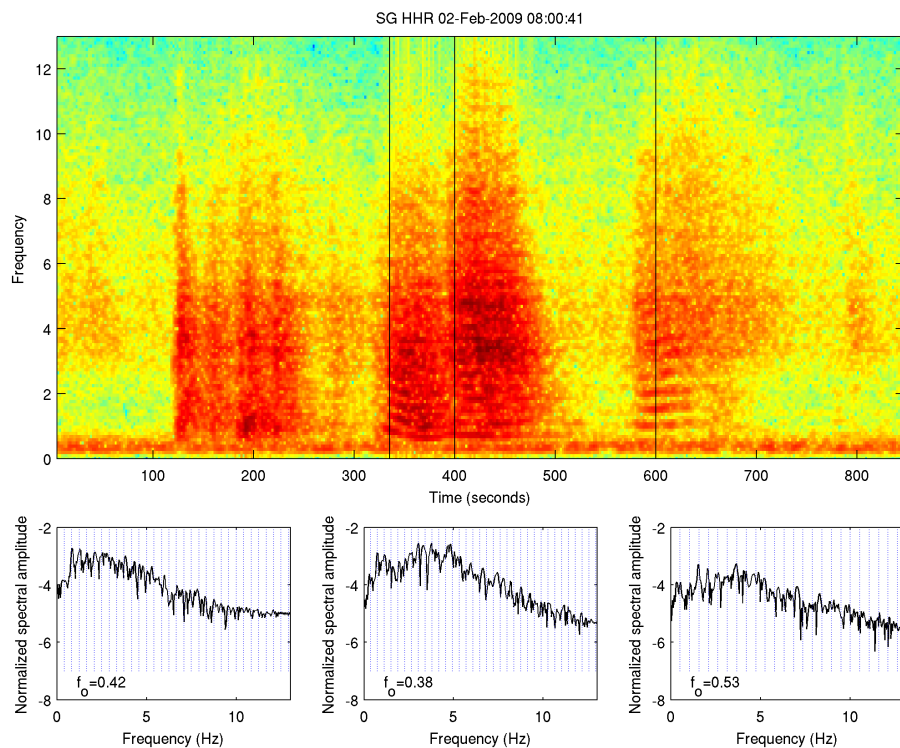
SG HHR 22-Jan-2009 12:31:40

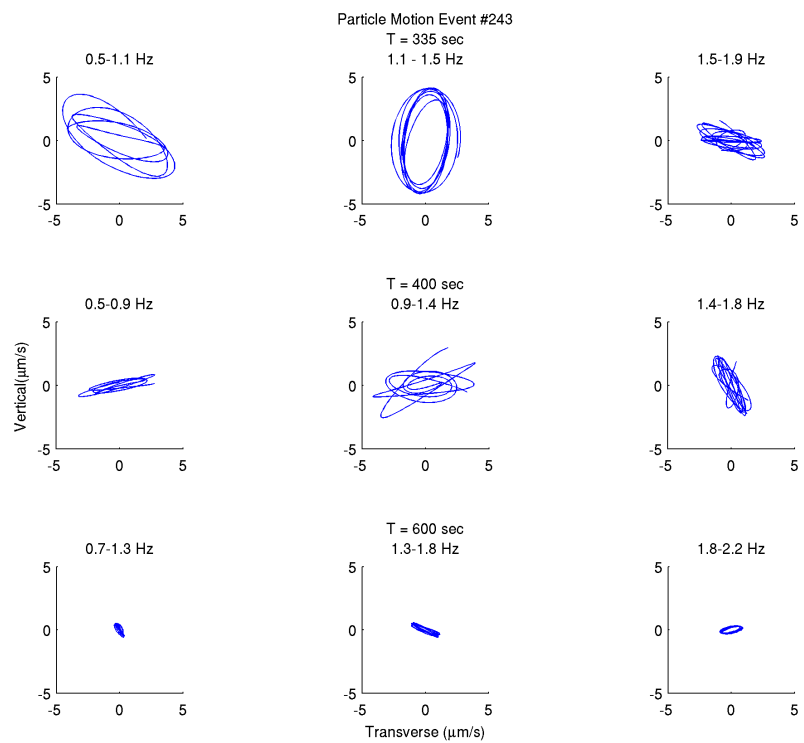
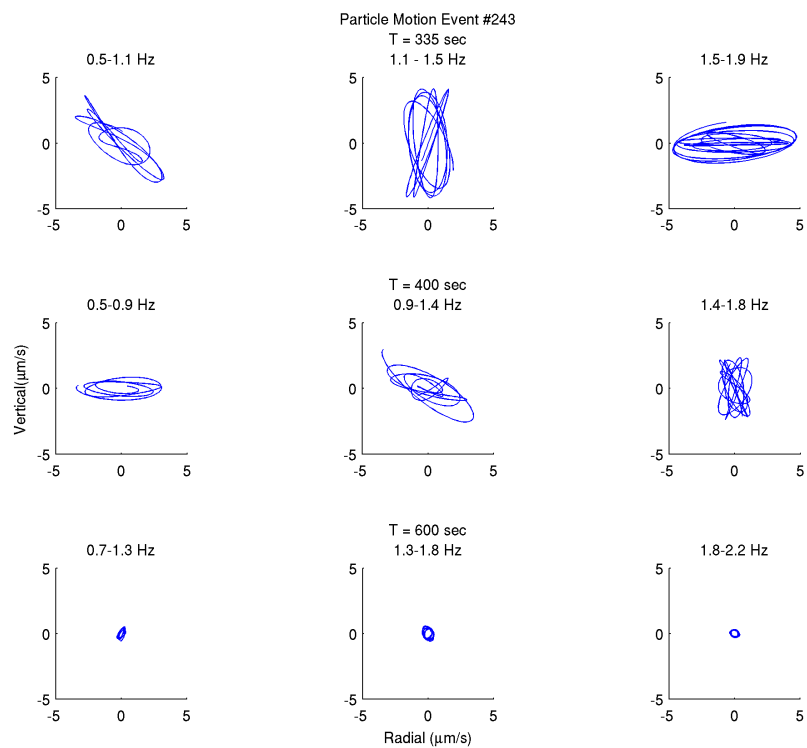




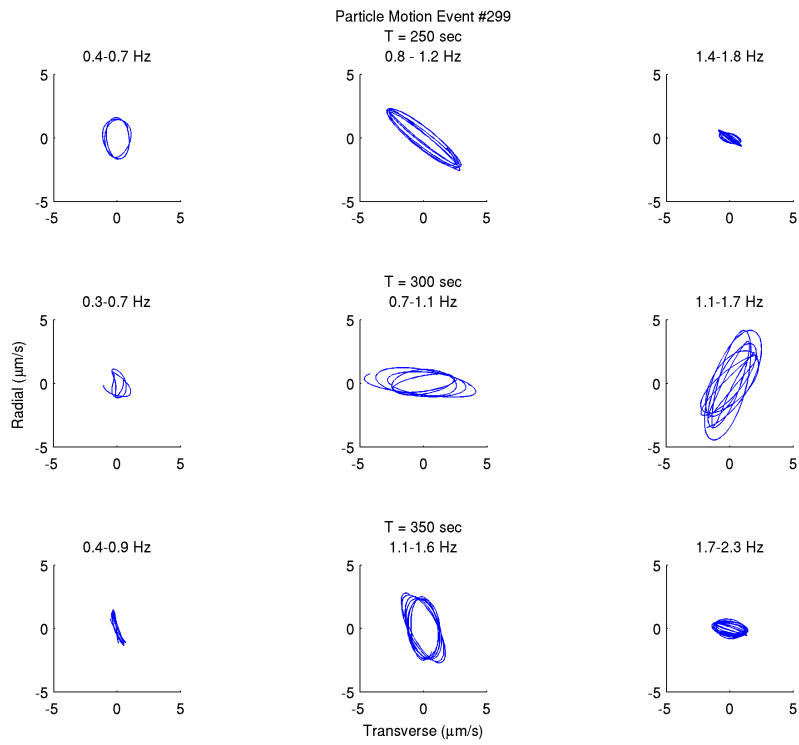
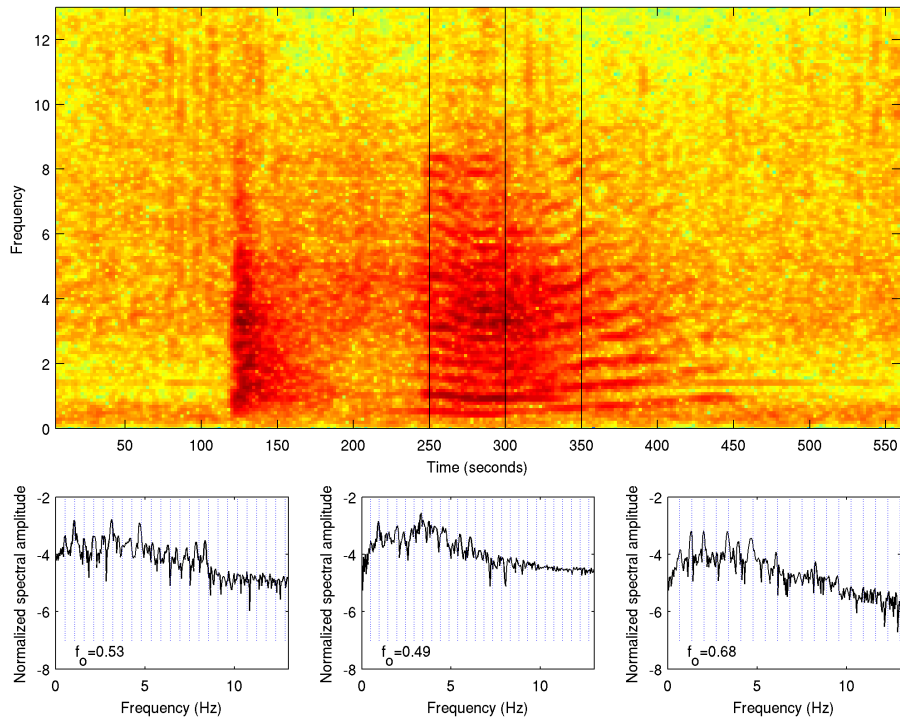


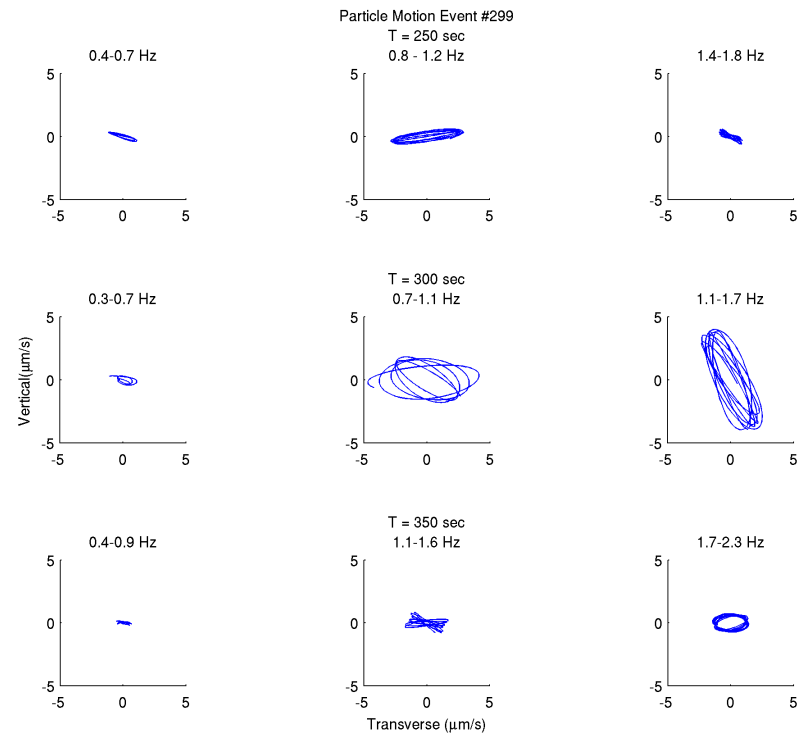
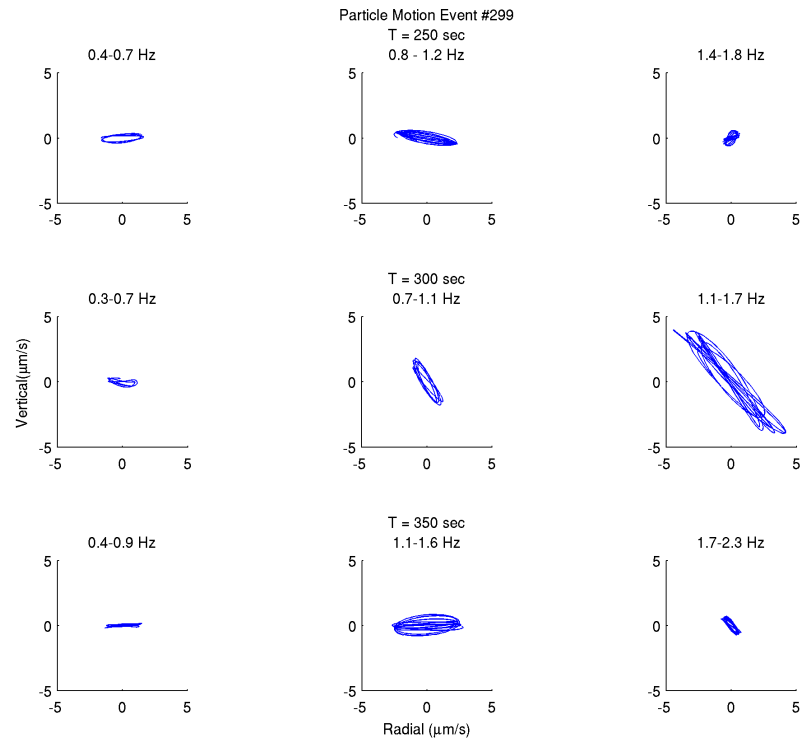




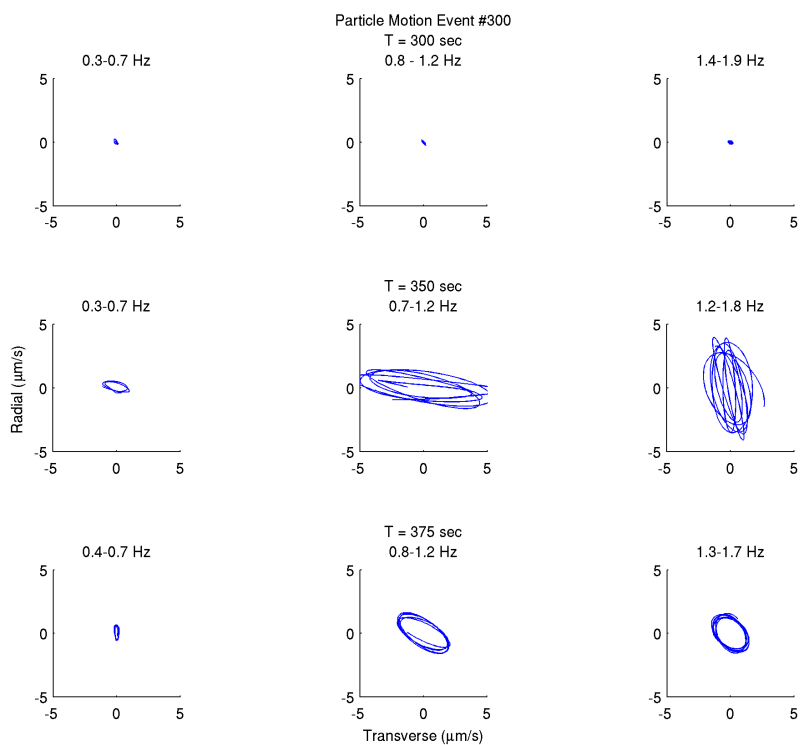
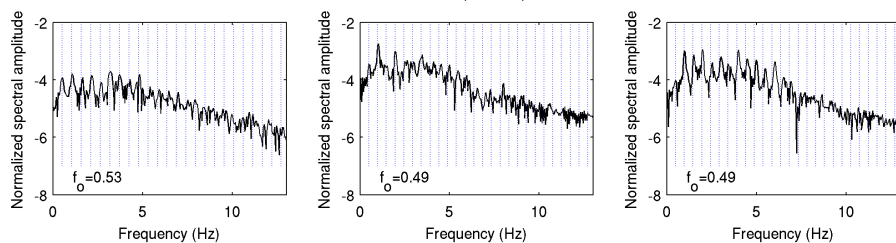
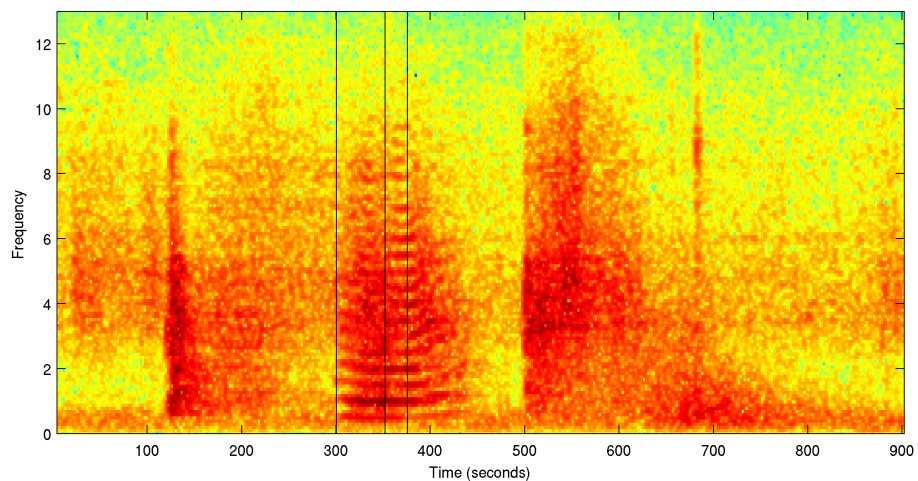


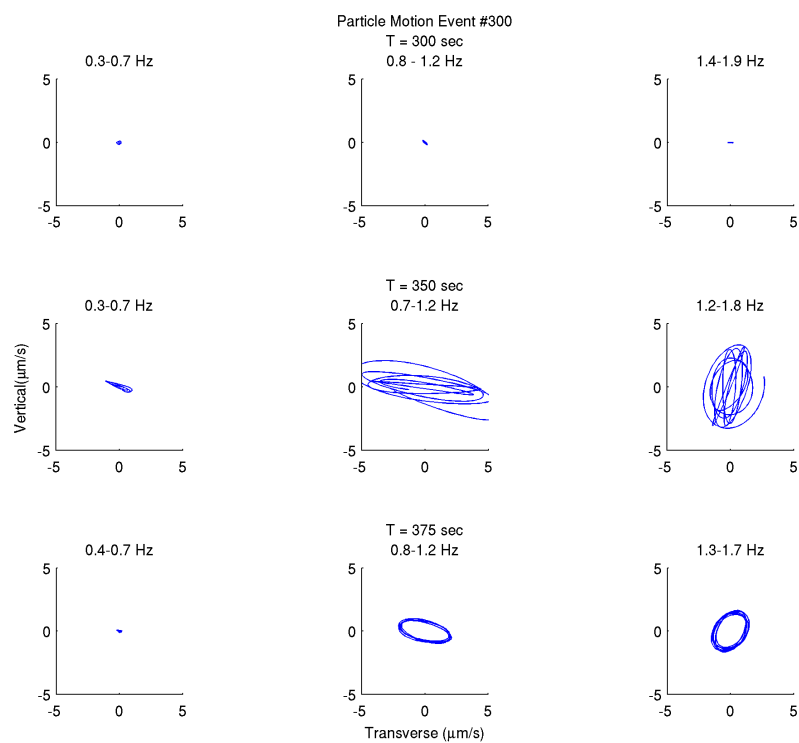
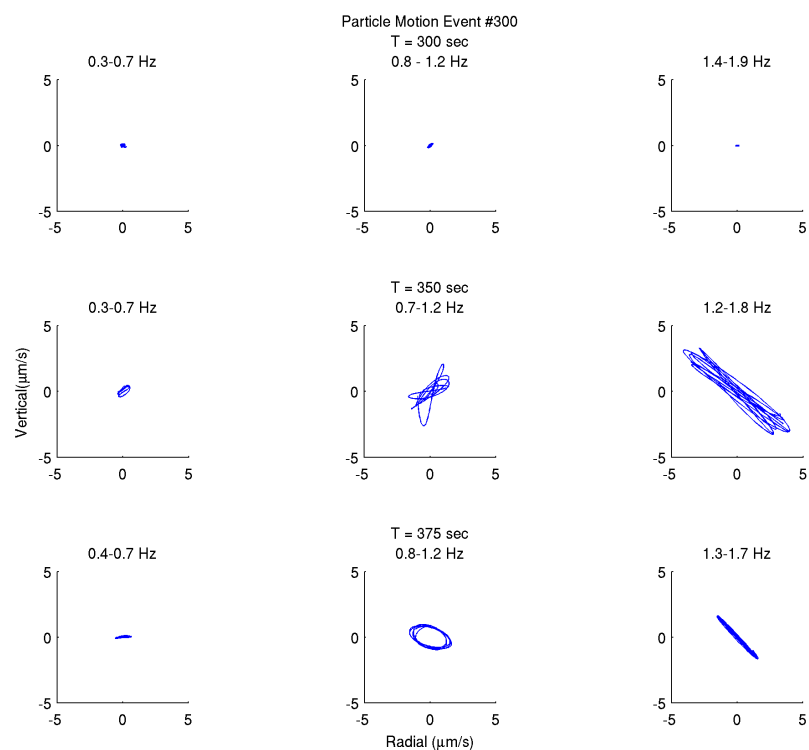
SG HHR 17-Mar-2009 01:01:57



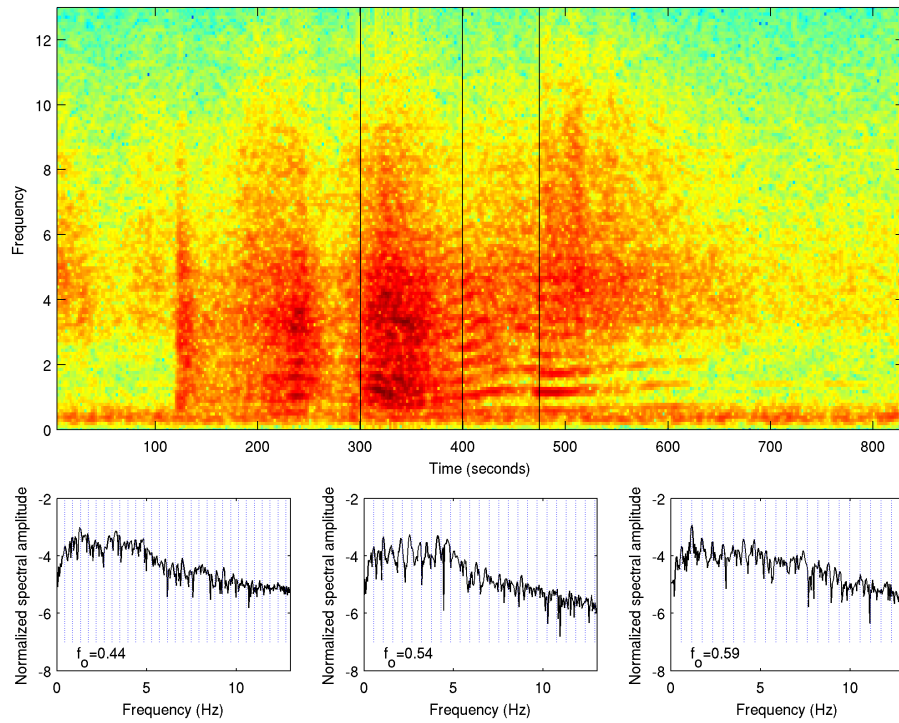


SG HHR 17-Mar-2009 02:25:10

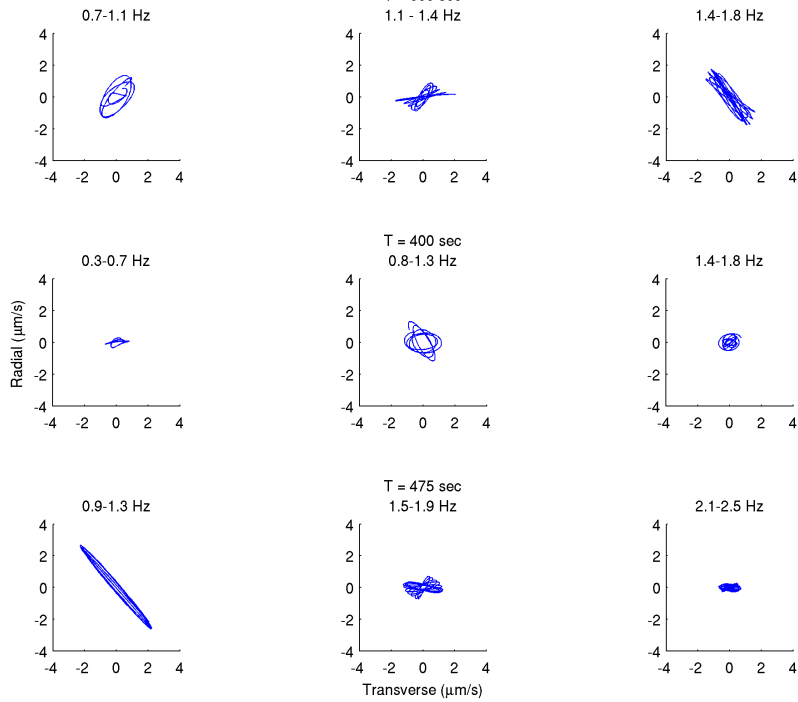




SG HHR 19-Mar-2009 08:57:01



Particle Motion Event #335
 $T = 300$ sec
 1.1 - 1.4 Hz



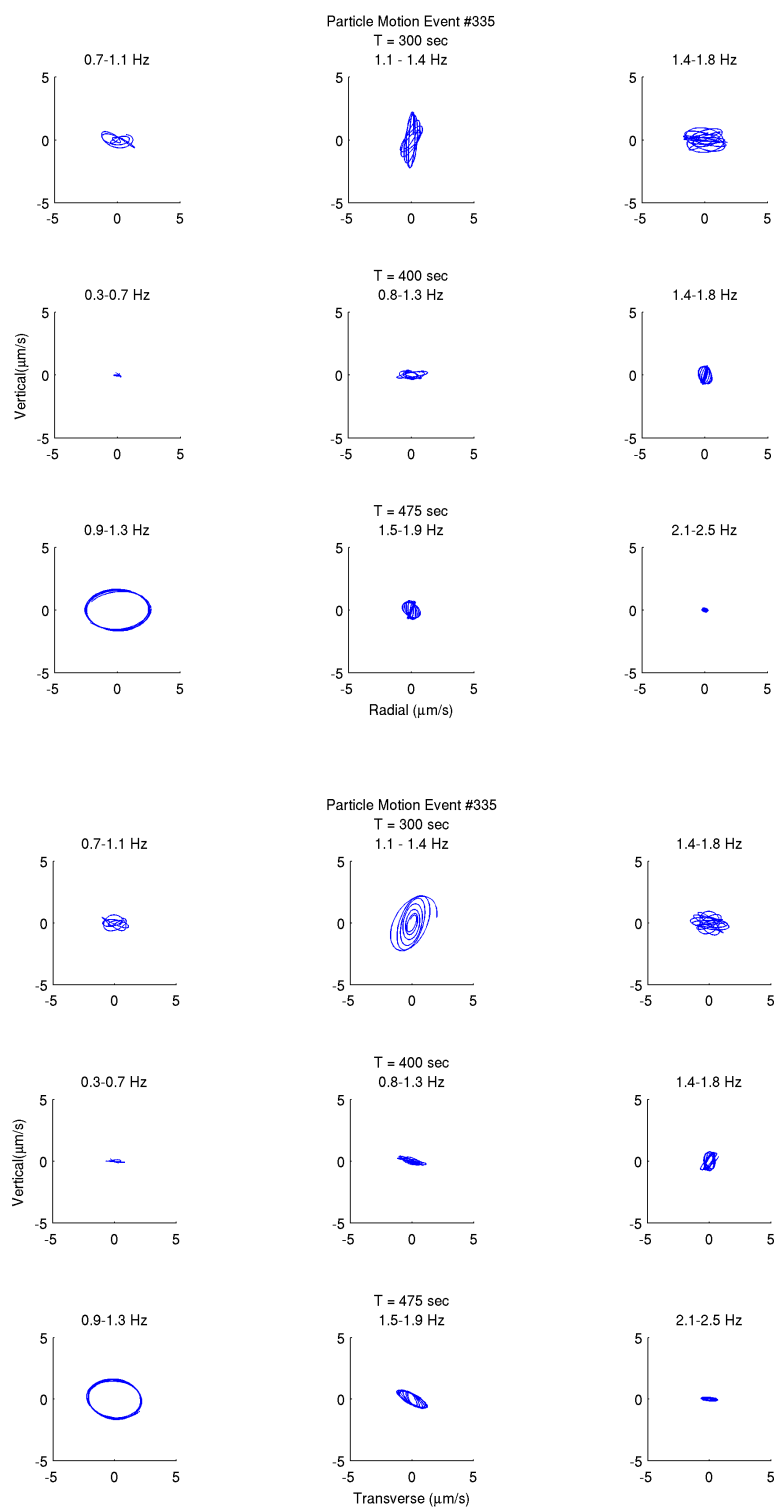
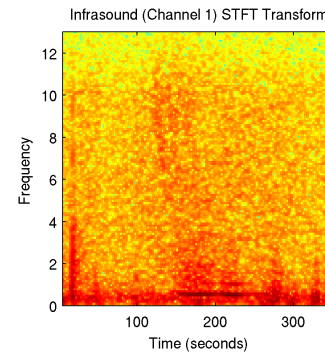
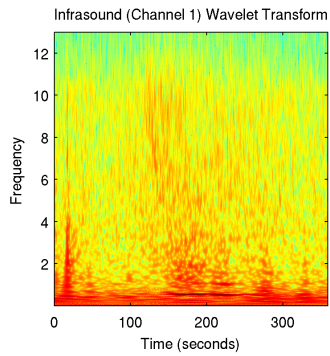
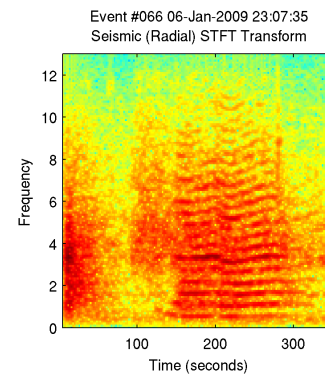
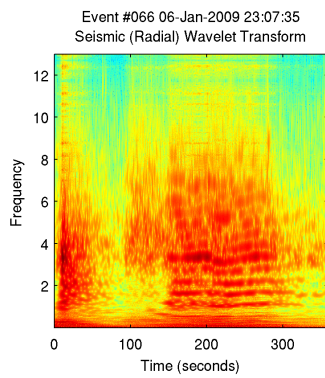
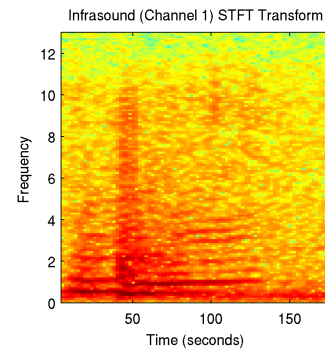
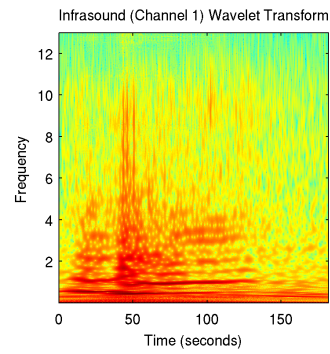
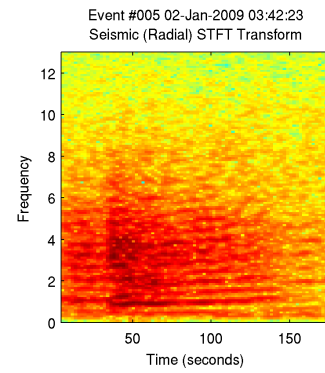
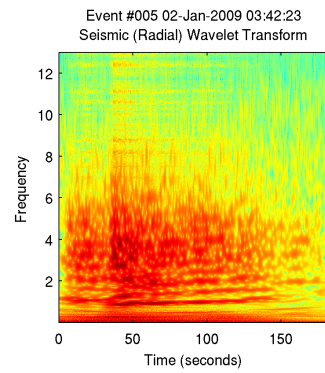
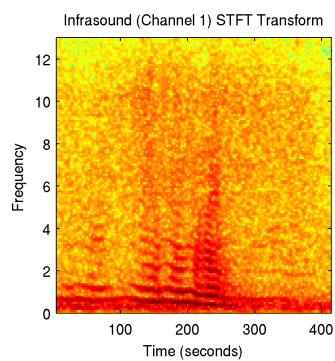
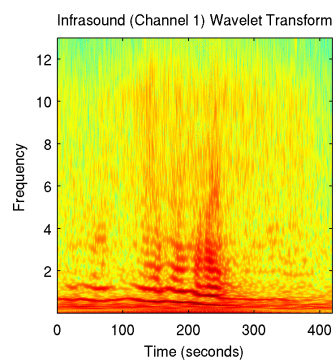
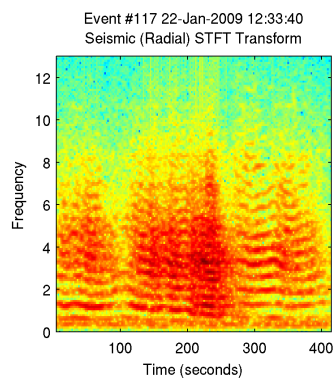
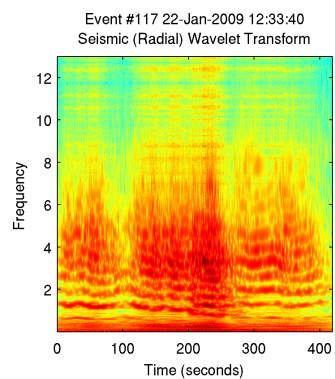
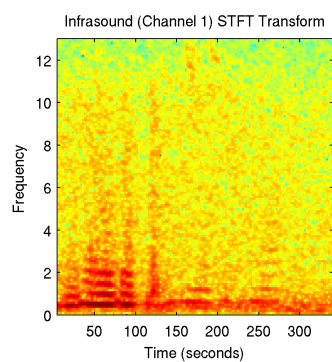
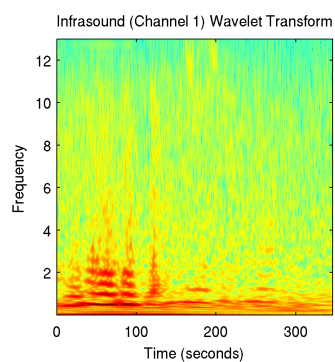
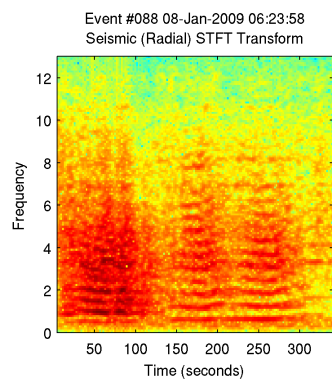
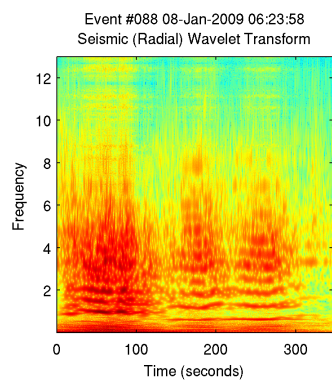
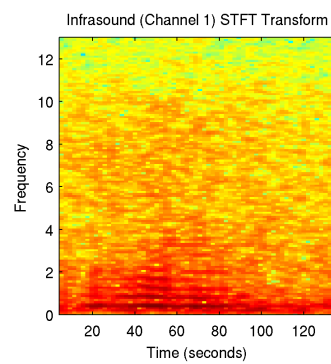
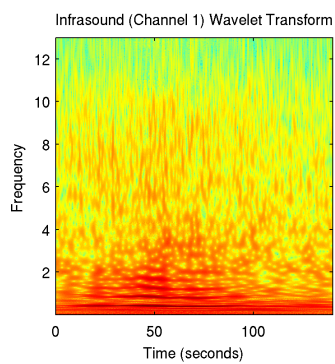
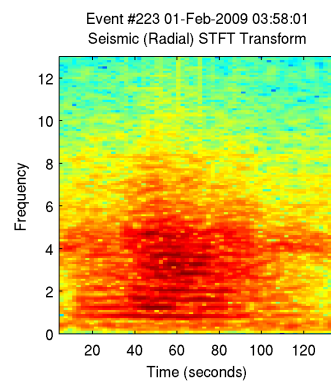
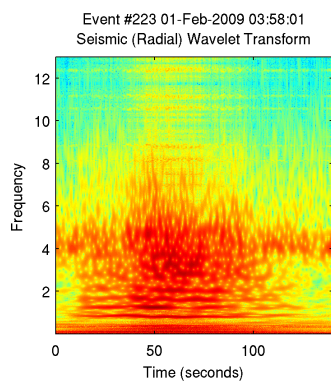
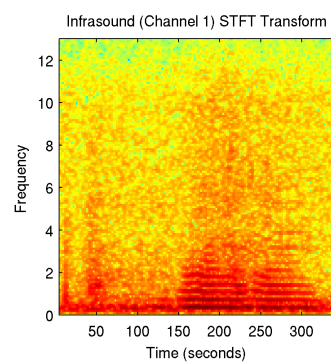
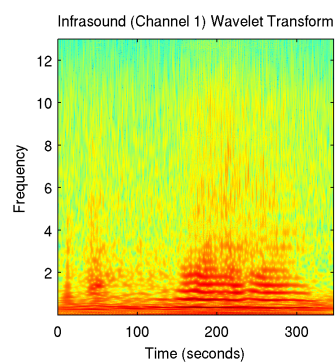
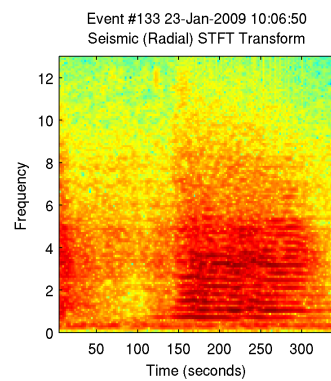
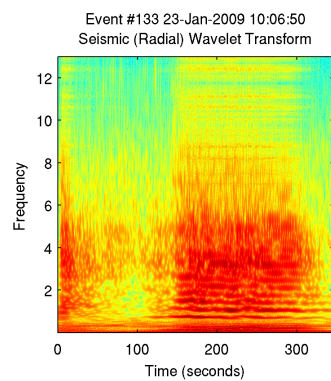


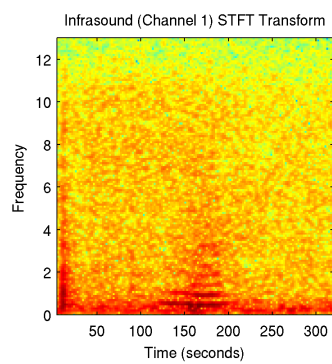
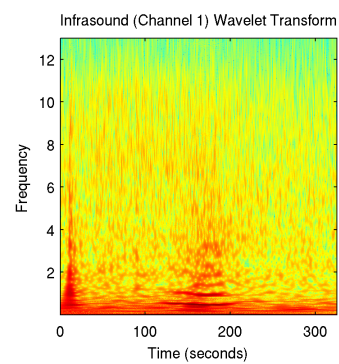
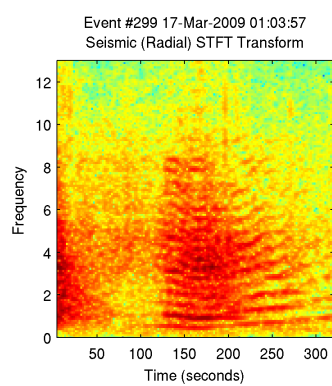
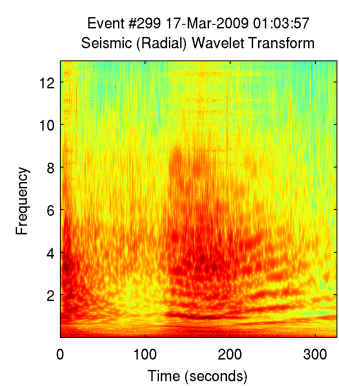
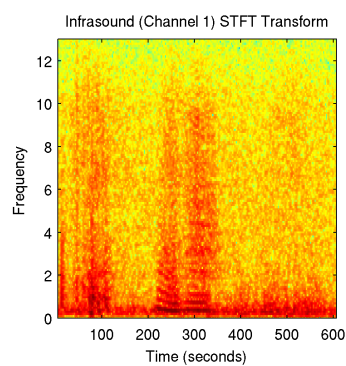
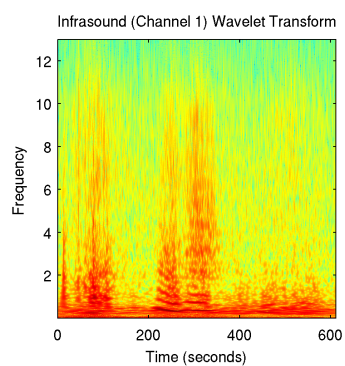
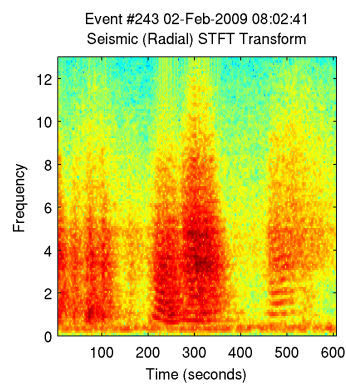
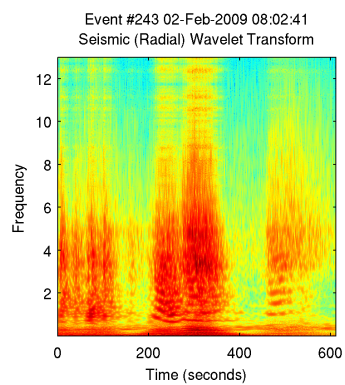
Figure 11.1: STFT and Particle Motion for Events from Appendix C

12 Appendix E: Wavelet Transforms with STFTs









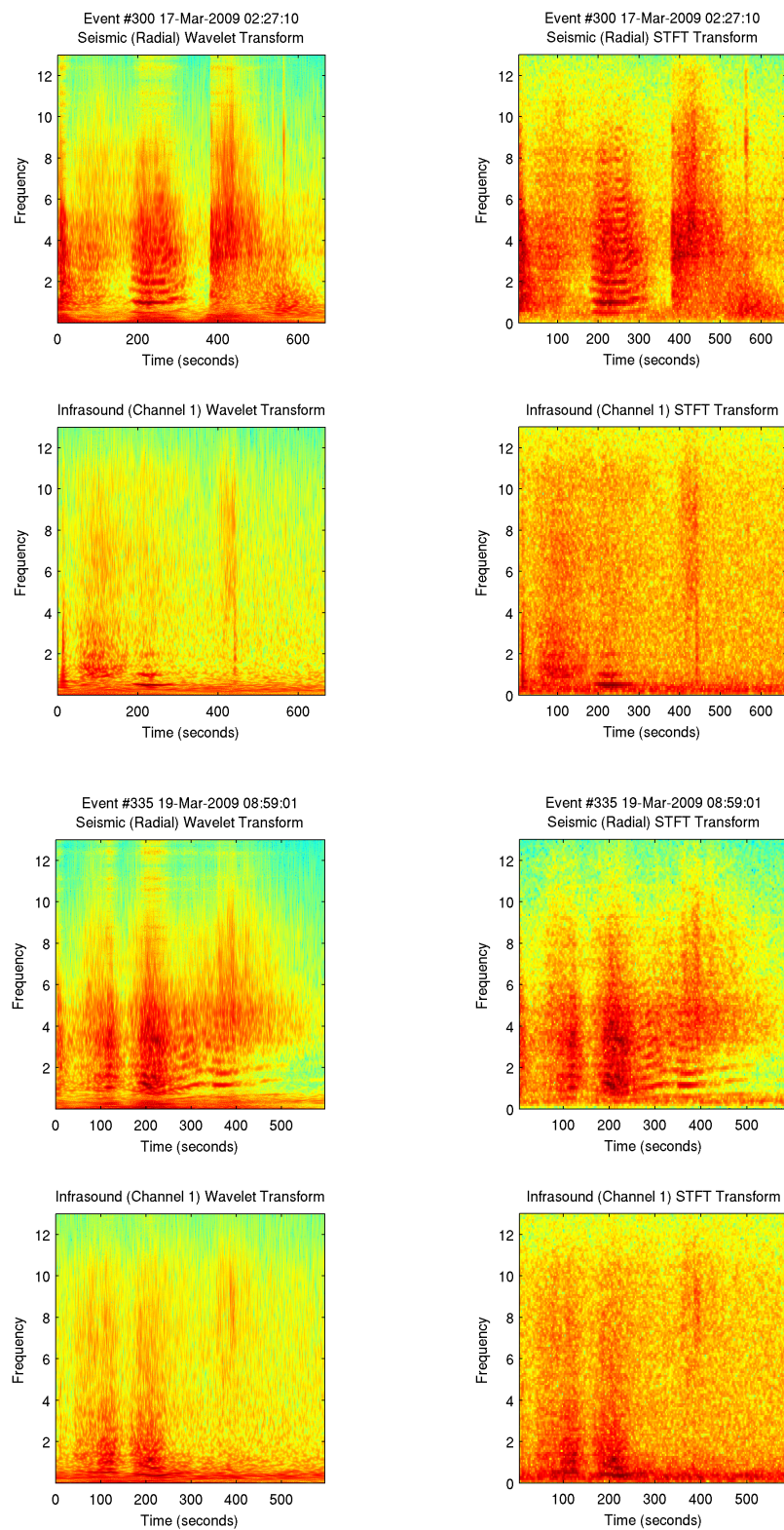


Figure 12.1: Wavelet Transforms with STFTs for events from Appendix C