A preliminary survey of the broadband seismic wavefield at Puu Oo, the active vent of Kilauea volcano, Hawaii

Dieter Seidl ([1]), **Margaret Hellweg** ([2]), **Paul Okubo** ([3]) **and Horst Rademacher** ([4])
([1]) *Seismologisches Zentralobservatorium Graefenberg, SZGRF, Erlangen, Germany*
([2]) *U.S. Geological Survey, Menlo Park, CA, U.S.A.*
([3]) *Hawaiian Volcano Observatory, Hawaiian Volcanoes National Park, HI, U.S.A.*
([4]) *57 Overhill Rd., Orinda, CA, U.S.A.*

Abstract
The seismic wavefield near an active volcanic vent consists of superimposed signals in a wide range of frequency bands from sources inside and outside the volcano. To characterize the broadband wavefield near Puu Oo, we deployed a profile of three three-component broadband sensors in a 200 m long line about 1.5 km WSW of the active vent. During this period, Puu Oo maintained a constant, but very low level of activity. The digital data logger recorded the wavefield continuously in the frequency band between 0.01 and 40 Hz between June 25 and July 9, 1994. At the same time, local wind conditions along with air temperature and pressure were monitored by a portable digital weather station. On the basis of characteristic elements, such as waveform, spatial coherence between stations, particle motion and power spectra, the wavefield can be divided into three bands. The dominant signals in the frequency band between 0.01 and 0.1 Hz are not coherent among the stations. Their ground velocities correlate with the wind speed. The signals in the 0.1 to 0.5 Hz band are coherent across the profile and most probably represent a superposition of volcanic tremor and microseisms from the Pacific Ocean. Much of the energy above 0.5 Hz can be attributed to activity at the vent. Power spectra from recordings of the transverse components show complex peaks between 0.5 and 3 Hz which vary in amplitude due to site effects and distance. On the other hand, power spectra calculated from the radial components show a clearly periodic pattern of peaks at 1 Hz intervals for some time segments. A further remarkable feature of the power spectra is that they are highly stationary.

Key words *volcano seismology – broadband volcano-seismometry – Puu Oo volcano*

1. Introduction

The seismic wavefield near an active volcanic vent consists of superimposed signals in a wide range of frequency bands from sources inside and outside the volcano. In the past, most investigations of the wavefield have used short period seismometers (for example, Koyanagi *et al.*, 1987; Schick, 1992). Only recently have broadband investigations begun to provide new insights into the wavefield and its volcanic origins (for example, Kawakatsu *et al.*, 1992; Neuberg *et al.* 1994; Hellweg *et al.*, 1994).

The Puu Oo vent of Kilauea volcano, Hawaii, which has been almost continuously active since 1983, is a steady source of seismic energy (Wolfe, 1988; Tilling and Dvorak, 1993). While several studies have investigated its wavefield (for example, Chouet *et al.*, 1987; Dietel *et al.*, 1989; Ferrazzini *et al.*, 1991; Goldstein and Chouet, 1994), prior to June 1994, no broadband measurements had been made in its vicinity. To address questions about the origin of the wavefield and to study seismic signals in the near-field of an active vent,

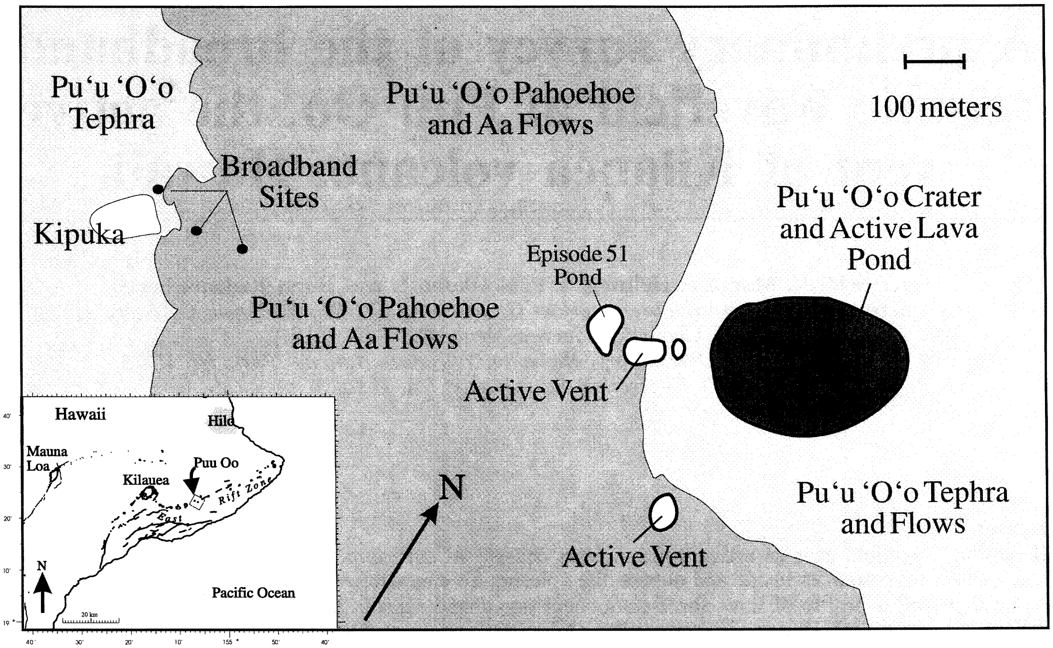


Fig. 1. Sketch of Puu Oo crater and active vents from June 1994. At the three sites, three-component broadband velocity sensors are located in a profile nearly radial to the direction of the Puu Oo crater. The reference station is AA1. The inset shows the location of Puu Oo in the East Rift Zone.

we deployed and operated three three-component broadband sensors near Puu Oo from June 25 to July 9, 1994. The signals recorded from these three closely spaced seismometers are processed using stacking techniques to eliminate long-period seismometer and wind noise while enhancing low energy, coherent, long-period signals which may emanate from the volcano.

Puu Oo is located in the East Rift Zone of Kilauea approximately 20 km E of the summit caldera (fig. 1, inset). Since January 1983 this vent has been almost continuously active. The eruption began with intensive lava fountaining and covered several square kilometers around the new vent with a thick tephra layer. During subsequent eruptive episodes the tephra was covered with layers of pahoehoe and aa lava.

Although lava from the Puu Oo vent continuously entered the ocean more than 10 km SE of the cone during June 1994, Puu Oo was seismically quiet with a stationary level of activity. The vent lay inside an approximately 250 m high cone and was filled with an active lava lake approximately 80 m in diameter. Thermal convection in the lake caused strong lava currents which sloshed almost continuously against segments of the crater walls. This activity generated an audible noise reminiscent of surf on a beach. In addition to the strong convection currents, the lava level in the lake sometimes rose and fell several meters over periods of less than an hour. Gases and steam were emitted from several side vents on the outer W slope of the cone, generating further acoustic emissions.

2. Deployment

The deployment site is located about 1.5 km WSW of Puu Oo (fig. 1) in the East Rift Zone of Kilauea. It is at the end of a pahoehoe flow which was partly covered by aa lava during a later episode. Both flows lie on top of the tephra field which stems from the early stages of the Puu Oo eruption.

The seismometers (Streckeisen, STS-2) were emplaced in a 200 m long line, nearly radial to the cone with each seismometer's nominal east component oriented approximately towards the vent. We call this the radial direction (R). The other component measures ground motion perpendicular to the direction of the vent, or approximately transverse (T). The instruments were about 100 m apart. Two of the three seismometers were situated in protected locations on the pahoehoe. The reference station, AA1, was deployed in a cast aluminum container firmly connected to a steel plate designed to reduce the broadband seismometer noise due to changes in air temperature and pressure at the site. The second pahoehoe site, AA2, was a small lava cave protected from the wind on the south side of the aa lava flow. Its seismometer was thermally insulated by wool inside an inverted bucket and hidden from solar radiation behind a loose wall of lava blocks. The third seismometer, TEPHRA, was installed on a metal plate in a *ca.* 70 cm deep hole in the tephra. It was shielded by a styrofoam insulated bucket and then covered with tephra. In spite of the different insulation techniques, all three seismometers remained remarkably stable in the very long period range during the three week deployment. Only once did we encounter drift that was not corrected by the internal feedback electronics of the instrument. The problem was caused by a weak battery and was easily resolved.

Data were recorded on a 6-channel PDAS data logger with an external hard disk and archived on magneto-optical disks. Because the PDAS has only 6 channels, during different intervals we recorded either the horizontal components from all three seismometers, or three components each from the reference station and one other station. In addition, we recorded wind direction and speed, air pressure, temperature and humidity at the site using a portable weather station.

The low level of seismic activity of the vent during this deployment and the various recording schemes allow us to address fundamental questions which must be answered before the results of measurements with broadband seismometers near active volcanoes can be reliably interpreted. The questions are:

1) How can oceanic microseisms be separated from low frequency tremor?

2) Do weather conditions affect the seismic signal?

3) Are there site effects due to the different substrates?

4) Is activity at the vent or in the volcano the source of all or most of the seismic signals in all frequency bands?

3. Observations

3.1. *The broadband power spectrum*

In fig. 2 the broadband velocity power spectra for the frequency band between 0.01 and 6 Hz are plotted for the vertical, radial, and tranverse components of ground motion at the reference station. The power spectra are estimated by segmenting the record, calculating a periodogram from each segment and averaging the periodograms. The spectra are then smoothed by taking moving averages around each spectral value. The degree of smoothing is three times higher for the radial and transverse components than for the vertical component.

The power spectra demonstrate that the energy recorded from the transverse component dominates at all frequencies, whereas the vertical component has the lowest overall level. Furthermore the power spectra may be divided into three characteristic frequency bands:

1) a very low-frequency band between 0.01 and 0.1 Hz with a plateau between 0.01 and 0.02 Hz. Towards higher frequencies the power level decreases linearly in a log-log plot up to 0.1 Hz;

2) a mid-frequency band beween 0.1 and 0.5 Hz with a dominant peak at 0.24-0.25 Hz for all three components;

3) the classical tremor band above 0.5 Hz with a complex fine structure and several peaks which vary in frequency for the different components.

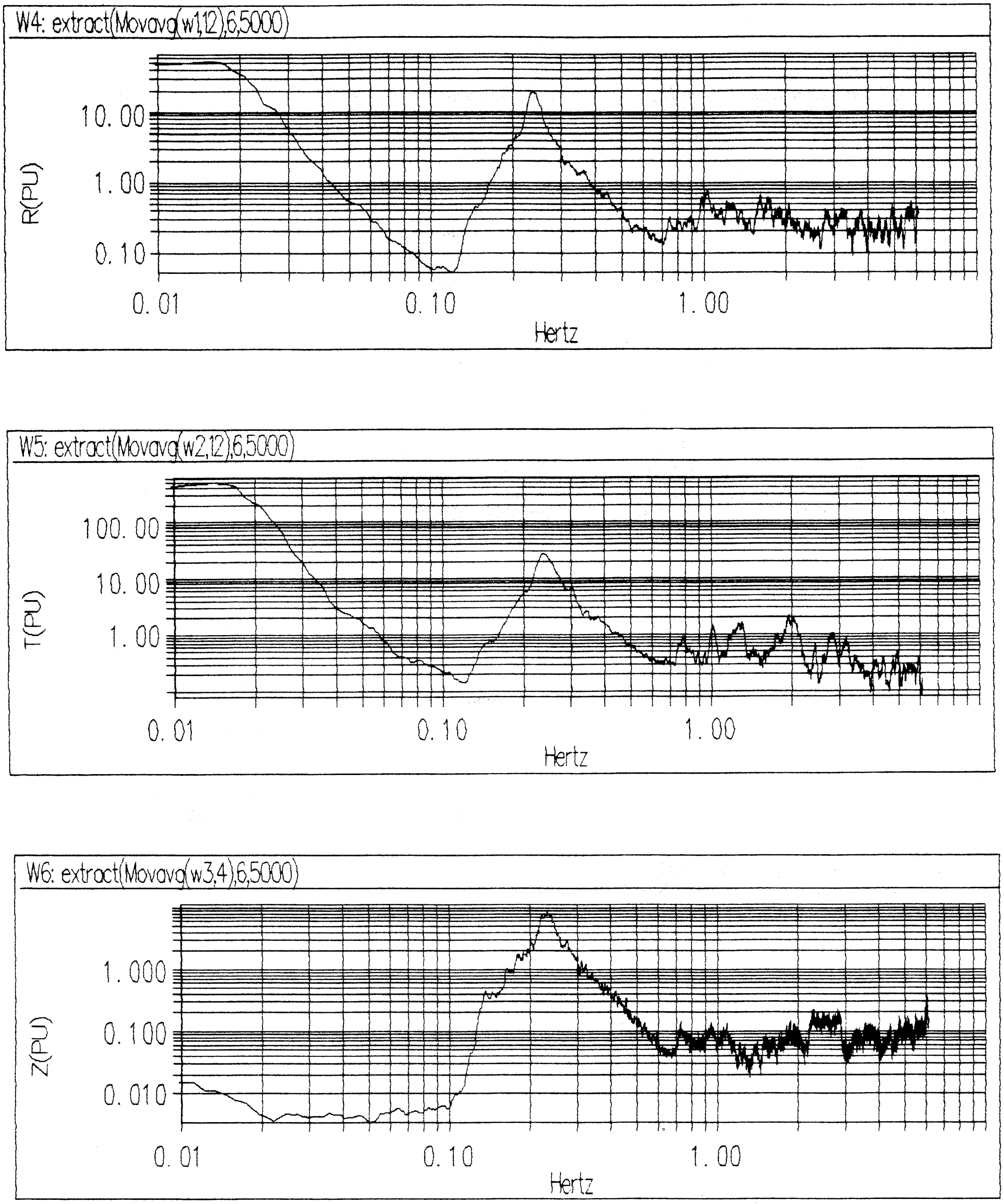


Fig. 2. Broadband periodogram power spectra of ground velocity for the radial (R), transverse (T) and vertical (Z) components for the reference station (AA1): seismometer period = 120 s; antialiasing filter = 8 Hz; sampling frequency = 20 Hz; number of segments = 10; length of segment = 16384 samples = 819.2 s; power unit PU = $(\mu m/s)^2/Hz$.

Above 6 Hz the spectral energy is correlated with wind bursts and narrow band tourist helicopter noise. Some energy in this range may be attributed to event-type volcanic signals. However, since the activity level was low during June 1994, it is difficult to distinguish between non-volcanic and volcanic sources, particularly during the day. For this reason we do not consider the frequency band above 6 Hz in this paper.

3.2. *The very low-frequency band, 0.01-0.1 Hz*

Propagating signals in this frequency band may be either of teleseismic or volcanic origin, while non-propagating energy must be caused by instrumental or meteorological sources. Since the interstation distances of about 100 m are much shorter than the wavelength for frequencies below 0.5 Hz, all propagating wave-groups should be coherent along the profile. On the other hand, non-propagating signals caused by local wind turbulence and temperature-induced seismometer noise should be spatially incoherent. For a profile of N stations, the coherent and incoherent components of the recorded signal can be separated by comparing the average of the N individual power spectra, ave(sp), with the power spectrum of the «delay-and-sum» beam trace, sp(beam). For frequency bands with completely incoherent traces the ratio, ave(sp)/sp(beam), is equal to N, the number of traces. We have excluded teleseismic sources by analyzing only segments of the dataset where surface waves from teleseisms are absent.

In fig. 3, a plot of averaged power spectra for the Puu Oo profile is compared with the

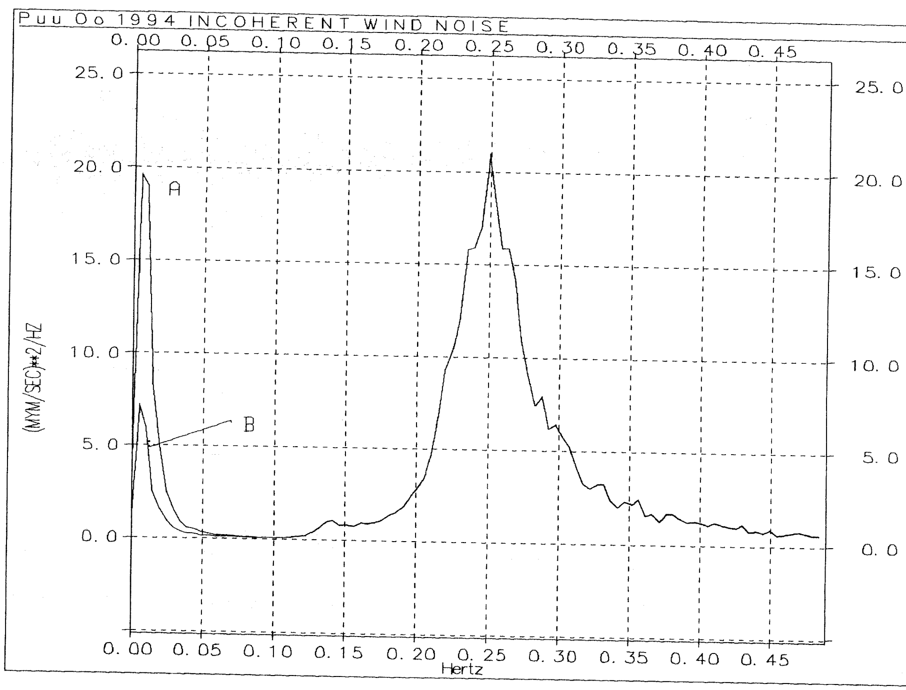


Fig. 3. Separation of spatially incoherent, non-propagating, very low-frequency ground noise from coherent, propagating parts by overplotting two power spectra A and B: A = average of the power spectra for the transverse components of the three seismometers; B = power spectrum of the averaged transverse components which have been beamed without delays. The power ratio at the very low-frequency maximum at about 100 s, A/B, is about 3, equal to the number of stations. This indicates non-propagating, incoherent noise.

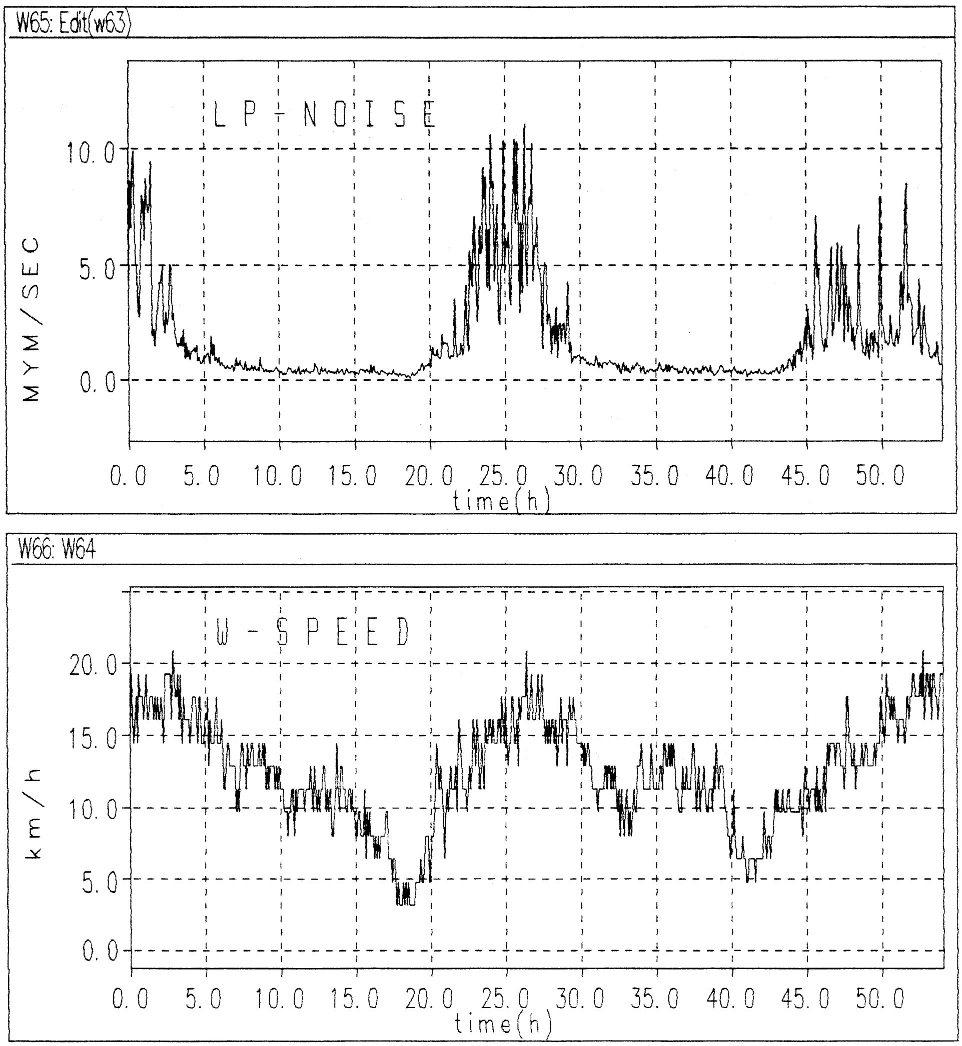


Fig. 4. Correlation between very low-frequency (LP) ground noise and wind speed (W) at the weather station for a time period of 54 h starting at 22:00 UTC on 01 July 1994. Hawaiian time is UTC-10 h. The ground noise is averaged over 5 min intervals corresponding to the sampling interval of the weather station.

power spectrum of the beam. The beam was calculated without applying time delays because the station separation is small compared to the wavelength. Spectrum A is the average power spectrum, ave(sp), of the three stations for the transverse component. Spectrum B is the corresponding power spectrum of the three-station beam, sp(beam). Above 0.05 Hz, the spectra are identical, while they diverge below 0.05 Hz. For the peak near 0.01 Hz spectrum A reaches a maximum of 19.5 $\mu m/s^2/Hz$, while the maximum of spectrum B is 7.0. The ratio of these two spectra is 2.8, or almost 3, which is the number of stations. This indicates that the coherence decreases below 0.05 Hz, and that the signals are nearly completely incoherent at 0.01 Hz. Thus, most of the energy below 0.05 Hz is due to incoherent, non-propagating signals.

The wind is the probable cause of signals in this frequency range. Hawaii lies in the trade wind belt where, in general, it is windstill during the night and the winds pick up during the day. In fig. 4 we compare the energy of the ground motion with the locally recorded wind speed. The wind speed is sampled as average wind speed over 5 min intervals. It is compared with the bandpassed velocity data from the transverse component of the reference station, also averaged over 5 min intervals, for the same 55 h period. These time series are strongly correlated, supporting the argument that wind is the main source for the energy in this band. Peterson (1993) and Asch (1994, personal communication) also note that wind can generate appreciable long period signals in the seismograms from broadband instruments. These observations are further substantiated by an investigation by Butler and Hutt (1992) on the atoll of Rarotonga in the South Pacific. They compare the long period seismic noise recorded at a surface seismometer with that recorded using a borehole seismometer and observe a clear increase in the level of seismic energy at the surface with increasing wind speed. At Puu Oo there seems to be a coupling threshold before the wind generates seismic energy. Long-period ground motion occurs only for wind speeds greater than 10 km/h.

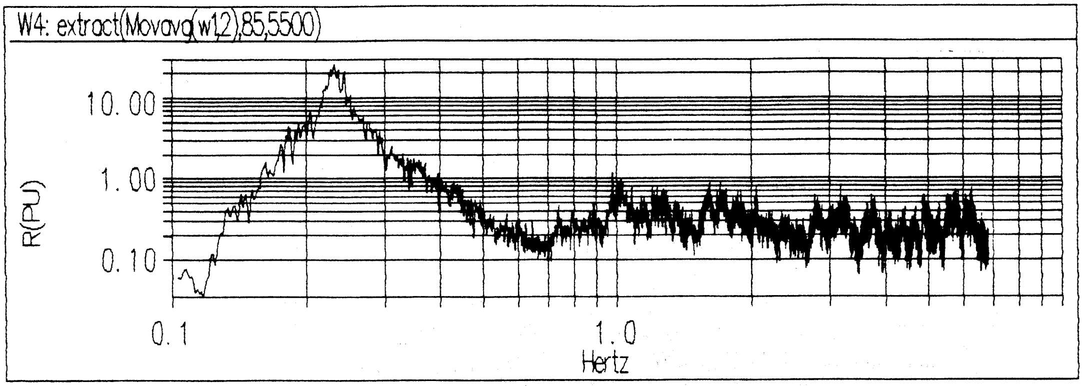
3.3. *The mid-frequency band, 0.1-0.5 Hz*

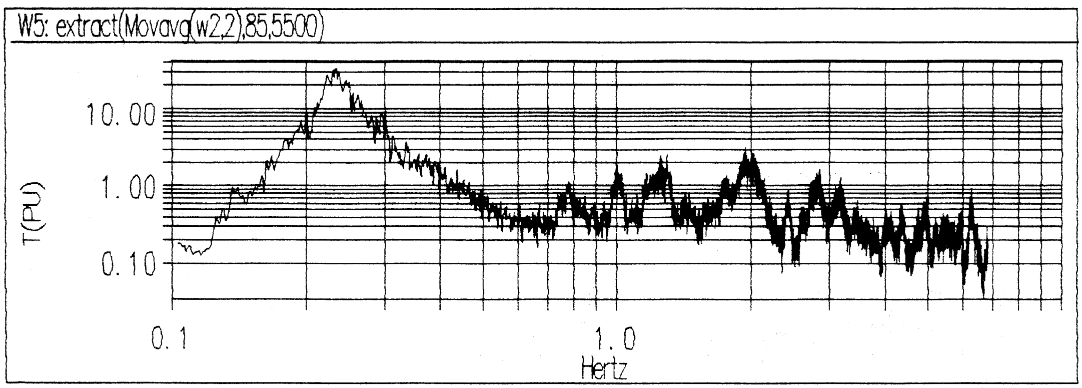
Due to the limitations of short period seismometers, until recently the most frequently used seismometers on active volcanoes, the transition of seismic energy from 1-2 Hz band towards lower frequencies is virtually unknown. For the three components of the reference station fig. 5 shows the power spectra above 0.1 Hz. These spectra have higher spectral resolution because the smoothing is less than in fig. 2. The broad, triangularly shaped maximum between 0.1 and 0.6 Hz is most probably the oceanic microseisms peak. In fig. 3 we have demonstrated that the energy in this peak is coherent at the three stations, because the spectral amplitudes of the beam and the summed traces are the same. Superimposed on both flanks of this peak in fig. 5, are small peaklets. While most of the energy in the wavefield for this band stems from the ocean microseisms, the energy generating the peaklets may be attributed to volcanic tremor.

Waveforms and the particle motion for a narrow frequency band (bandpass filtered from 0.2 to 0.28 Hz) around the spectral peak at 0.24 Hz are plotted in fig. 6 for the radial and transverse components of the reference station. The spectra for both components have similarly shaped, low-frequency slopes and pronounced peaklets at different frequencies on the higher frequency slope. The beat pattern which dominates the recording of the radial component can also be distinguished in the transverse record. It is not nearly as pronounced on the transverse component, however, because other wavegroups occasionally blur its pattern.

The particle motion diagram helps to understand this structure. In this narrowly filtered frequency range, the wavefield in the horizontal plane seems to contain two distinct polarization patterns, one of which is dominant and highly stationary in time. In this dominant pattern nearly all energy is concentrated in the transverse direction, which indicates that these waves continuously arrive at the measurement site from the same direction, very likely from the volcano. The other pattern has a rapidly and randomly changing elliptical polarization. This pattern is generated by seismic surface waves arriving at the site from various, randomly distributed directions. With a linear configuration, we cannot determine the sources of these random waves using array techniques. We assume, however, that they represent the oceanic microseisms and are not generated by the volcano.

The wavefield in the mid-frequency range warrants further, more detailed investigation. A combination of bandpass filtering and polarization analysis can separate it into its constituent parts.





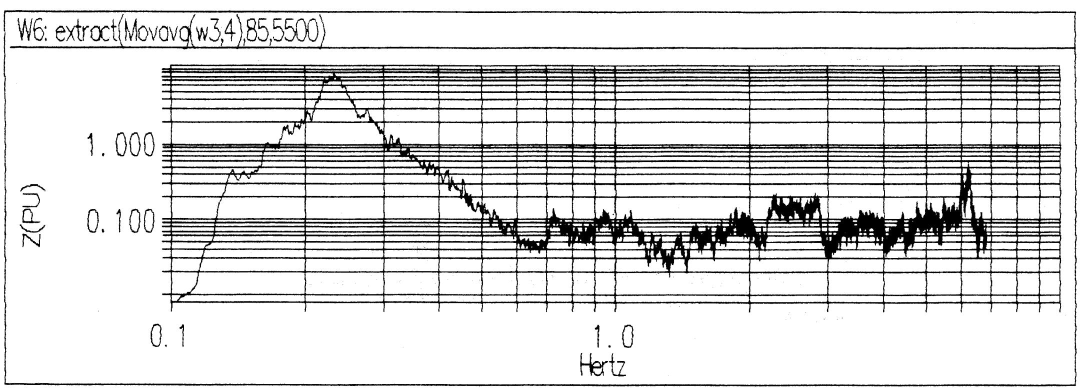


Fig. 5. Excerpt from the power spectra in fig. 2 for the mid-frequency and classical tremor bands with less smoothing. The frequencies of the dominant peaks for the transverse band in the classical band are: 0.78 Hz, 1.03 Hz, 1.30 Hz and 1.95 Hz

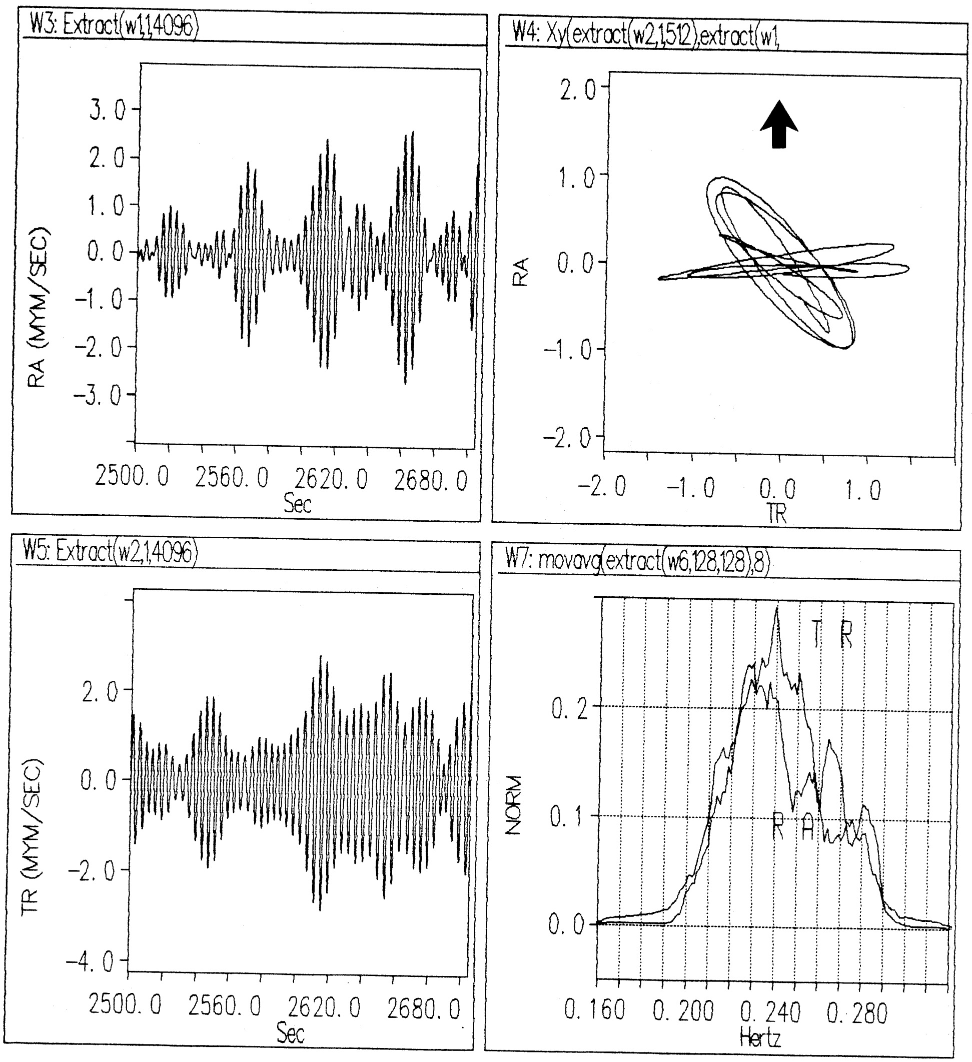


Fig. 6. Bandpass-filtered seismograms of the radial (RA) and transverse (TR) components for the mid-frequency peak in fig. 5. The accompanying particle motion diagram shows the polarization for a segment of this interval. The amplitude spectra show tremor peaklets superimposed on the broad microseism peak.

3.4. *The classical tremor band*

Narrow-band peaks are the most remarkable feature in the power spectra of tremor above 0.5 Hz at Puu Oo, the band usually recorded with short period seismometers. The peak frequencies are characteristics used for monitoring the activity state of the volcano and are also commonly used as input for modeling the tremor source. Surprisingly, the peaks occur at similar frequencies at many different volcanoes (for a review, see Julian, 1994), suggesting that the basic physical mechanism which produces them may be universal.

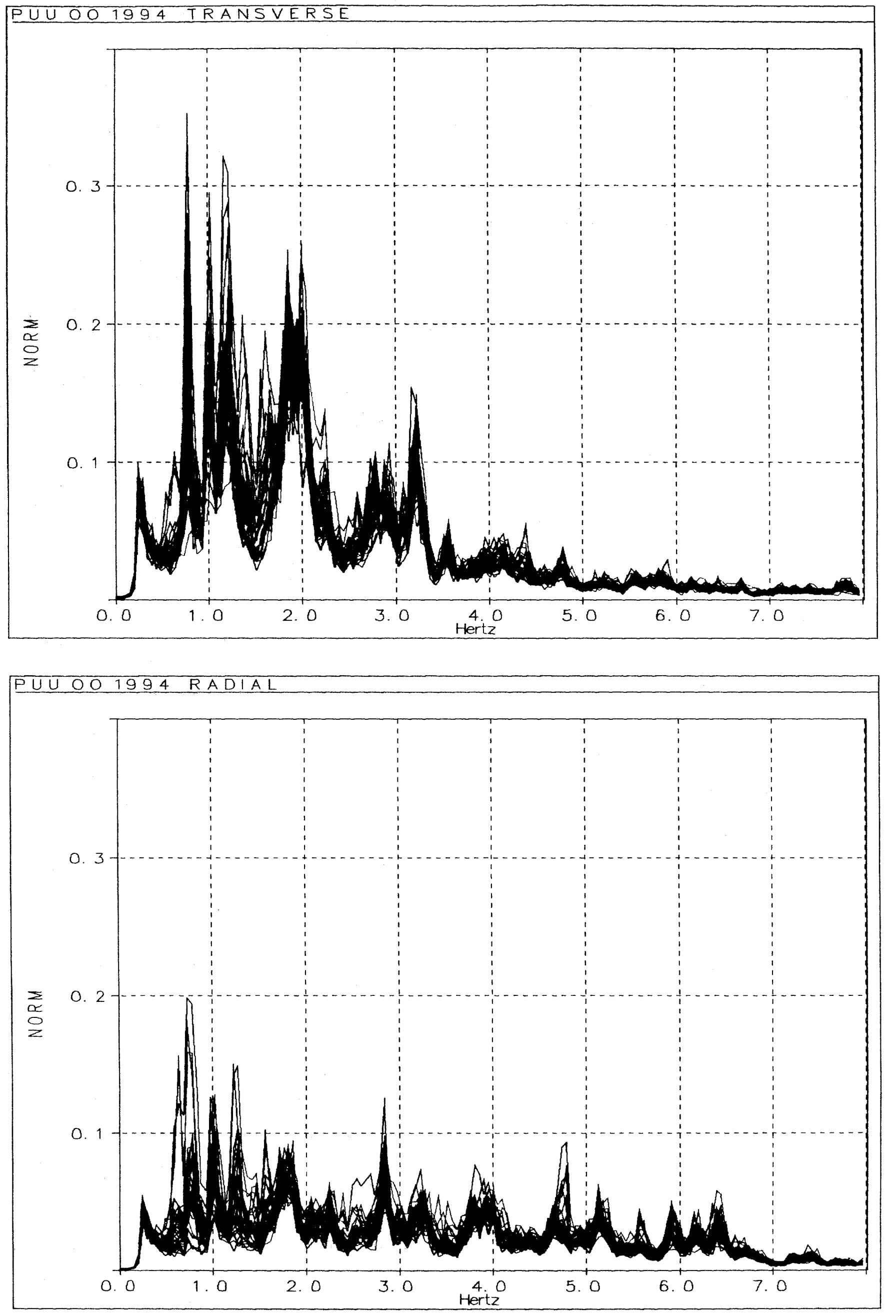


Fig. 7. Highly stationary tremor in the classical band above 0.5 Hz: overplot of normalized (NORM) short-period power spectra for a 43-h time interval for the transverse and radial components of the reference station.

A basic condition in the estimation of power spectra by averaging the periodograms of a sequence of data segments is the assumption that the time series is stationary. One method to test this assumption is to plot power spectra of the segments to be used on the same frame. This has been done for the Puu Oo data in fig. 7. While the amplitudes of the peaks fluctuate, there is remarkably little variation in the frequencies of the peaks. Thus, the process generating the peaks is stationary.

At the three seismometer sites, with different coupling, the averaged power spectral amplitude of the classical low-frequency peaks varies, presumably due to site effects (figs. 8 and 9). Around 1 Hz, the group of three peaks is apparent at all sites and on both the transverse and radial recordings. Although the peaks for either the transverse or radial recordings are present at all sites, for increasing frequency, the variation in amplitude increases. Occasionally, the peak frequencies recorded at all three sensors undergo slow correlated changes. Thus, the amplitude variation may be caused by the site, but the frequencies at which the resonances occur are probably determined by the source.

A non-stationary phenomenon in the recordings at Puu Oo are sequences of short-term power spectra where the frequencies of the peaks are periodic (fig. 10). This is particularly apparent in the contour diagram of the time-frequency spectrum (bottom). Over the interval shown here, the peaks appear be excited randomly. On closer inspection, bands of peaks appear on this plot at the frequencies represented in the long-term power spectrum (top). This phenomenon is different from the simple, harmonic peak signature seen at some volcanoes (Mori *et al.*, 1989; Hellweg, *et al.*, 1994), in that it appears to be a harmonic series of multiplet peaks.

4. Conclusions

In the very low-frequency band between 0.01 Hz and 0.1 Hz it is necessary to separate the recorded signals into propagating waves and non-propagating noise. The propagating waves originate either in the volcano or are generated by teleseismic earthquakes. The non-propagating noise may either be of instrumental origin, *i.e.* from convection or temperature variations in the seismometer, or may be caused by the interaction of the wind with the ground.

Propagating and non-propagating signals can be resolved by their respectively characteristic spatial coherence. Ideally, for studies in this frequency band, a deployment would involve at least two sensors at distances much smaller than the wavelengths of the signals, a far-field sensor and a local weather station. The propagating and non-propagating components of the wavefield can be separated by comparing the signals at the two closely-spaced stations. The propagating wavegroups from the volcano will probably have different characteristics at the far-field station than in the near-field, while teleseismic waves will be coherent at both stations. The non-propagating component can only be recognized by circumstantial evidence. If it correlates with variations in wind speed or other weather parameters, it is probably a weather-related phenomenon. Otherwise, it must be associated with thermal noise in the seismometers.

At Puu Oo, the very low-frequency peak found between 0.01 and 0.02 Hz is noise induced by the wind. The energy in this band is incoherent and therefore non-propagating, as is shown by comparing the averaged power spectra of three stations with the power spectrum of the beamed seismograms (fig. 3). The level of the power of the ground motion recorded in this band is correlated with changes in wind speed. If there are low energy volcanic signals in this frequency band, they can be enhanced by stacking techniques applied to segments of the recordings of the three sensors.

Energy in the mid-frequency band between 0.1 and 1.0 Hz may also be generated by several sources. The most important of these are volcanic tremor and oceanic microseisms. To resolve the wavefields from these sources, an experiment needs three-component sensors to permit polarization analysis, as well as a far-field station. In the polarization analysis we seek to resolve the recorded wavegroups into

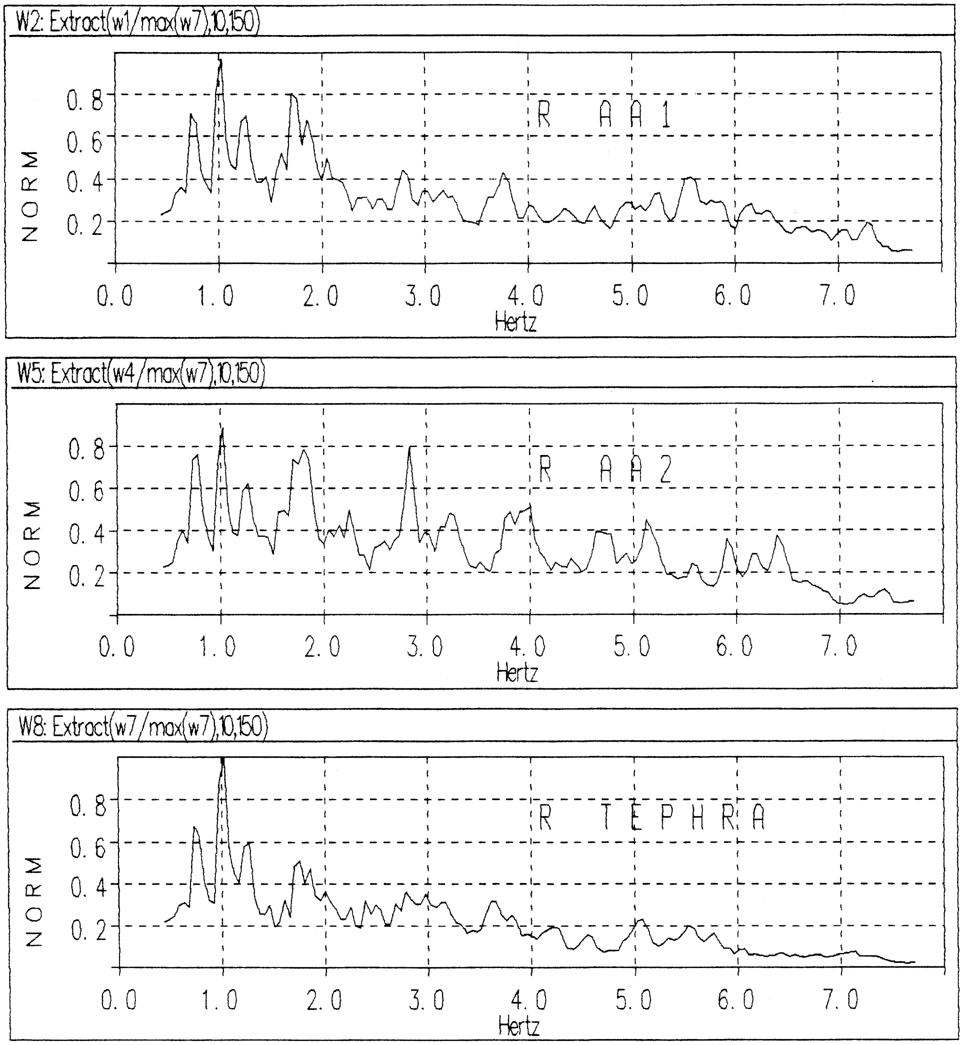


Fig. 8. Normalized (NORM) short-period power spectra demonstrating site effects for the radial (R) components of the reference station, AA1, the second pahoehoe station, AA2, and the tephra station, TEPHRA.

two parts, one with stable polarization transverse or radial to the direction of the volcano and one with variable polarization. An additional indicator for the sources of these wavegroups is the correlation of their signal level either with volcanic activity or weather systems which might generate increased oceanic microseism activity.

In this band, narrow peaklets are superimposed on a broad, dominant peak in the power spectra measured at Puu Oo. The peaklets appear to be a continuation of the classical tremor peaks between 1 and 5 Hz to lower frequencies. In the particle motion diagram, there are wavegroups with stable polarization transverse to the direction to the Puu Oo vent, while

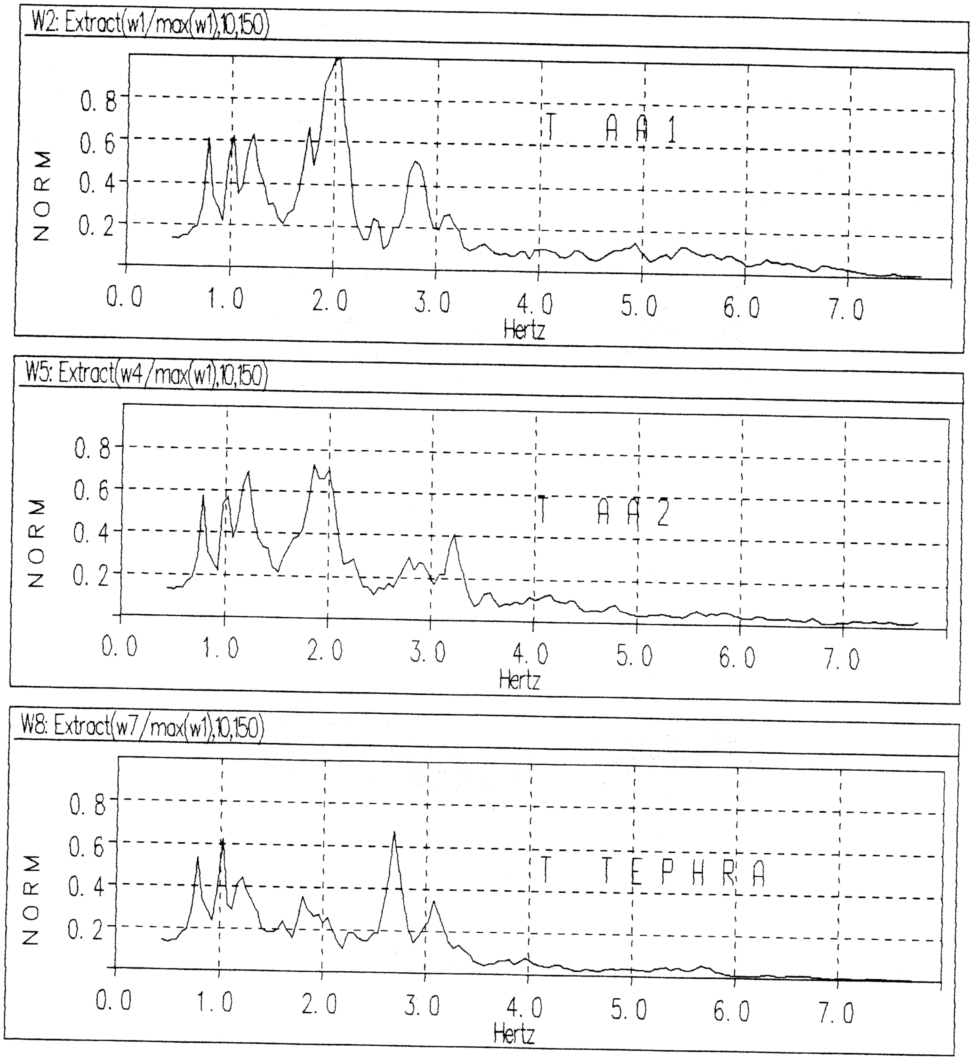


Fig. 9. Normalized (NORM) short-period power spectra demonstrating the site effects for the transverse (T) components of the stations AA1, AA2 and TEPHRA.

the polarization of other wavegroups changes direction randomly over all azimuths. The wavegroups with the stable transverse polarization are probably generated at the vent, or at some other nearby source along East Rift Zone, such as the Steamcracks, while the randomly polarized signals are probably oceanic microseisms.

During the broadband experiment at the Puu Oo vent, the seismic activity was low, but extremely stationary. As a result, power spectra of the tremor in the classical low-frequency band between 1 Hz and 10 Hz are typical of those observed at many volcanoes. The peak frequencies undergo slow correlated changes at all three sensors, indicating that the variations

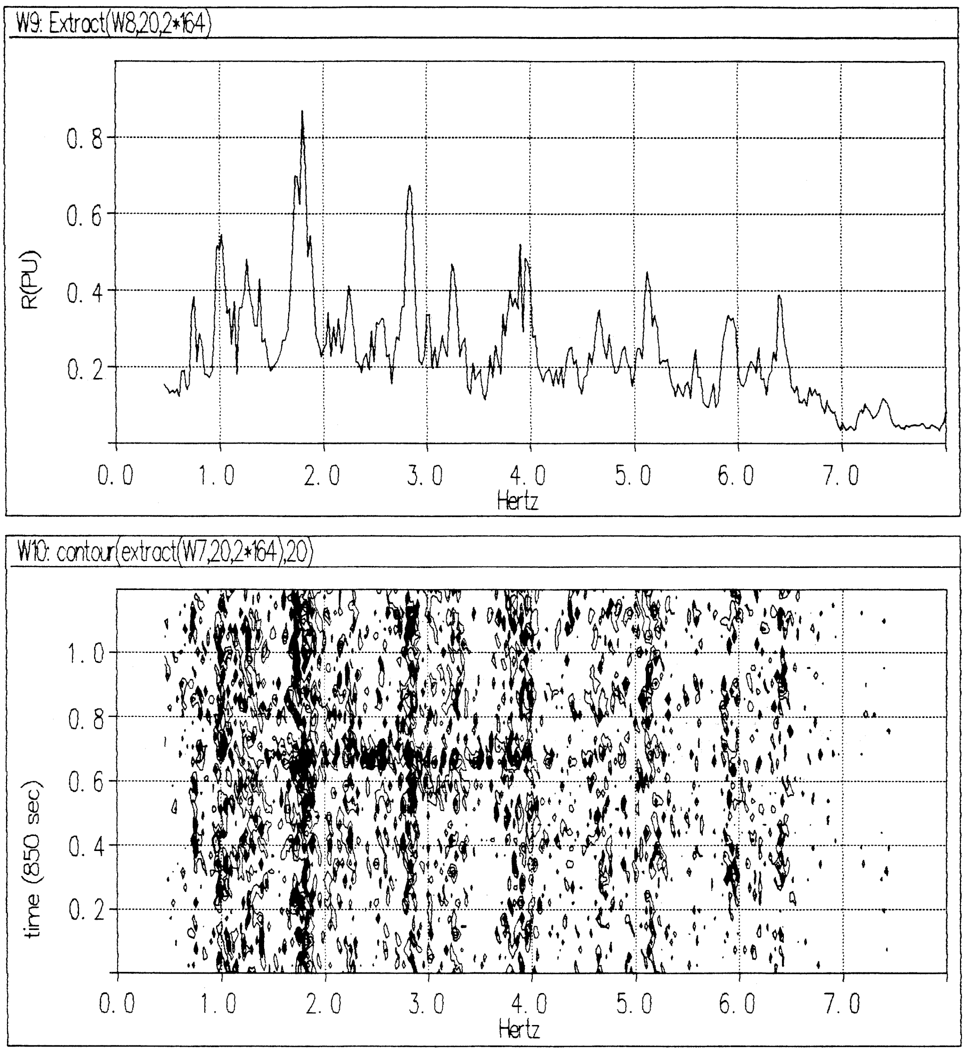


Fig. 10. Short period power spectrum (PU units as in fig. 2) and time-frequency power spectrum with cyclic overtone pattern.

are probably generated at the source and are not caused by propagation effects. Near 1 Hz the site effects appear to be relatively small, so that measurements of attenuation of source depth through amplitude-distance curves in this band will probably be less affected by sitefactors.

The periodic pattern of multiplet peaks (fig. 10) is different from the simple, harmonic peak signature observed at the volcano, Mt. Semeru (East Java, Indonesia), (Hellweg *et al.*, 1994). It appears to be a harmonic series of multiplet peaks. For Semeru, the source of the harmonic tremor has been modeled as a simple, resonating gas column (Schlindwein *et al.*, 1995). The active vents at Puu Oo continuously produce turbulent steam columns. It is possible that the coupled activity in these vents is the source of the multiplet spectral peaks.

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