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BICHROMATIC EXCITATION OF LONG-PERIOD RAYLEIGH AND AIR WAVES BY THE MOUNT PINATUBO AND EL CHICHON VOLCANIC ERUPTIONS

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Abstract. We have detected a new powerful source of low-frequency seismic energy which is associated with some violent volcanic eruptions. For the two eruptions for which we have identified this new source the spectrum is bichromatic, consisting of two narrow, phase coherent spectral lines. These bands were centered on 3.76 and 5.14 mHz for the April 4, 1982 El Chichón eruption, and on 3.68 and 4.44 mHz for the June 15, 1991 Mt. Pinatubo eruption. During the latter, 8 hour long eruption the resonance frequencies varied by less than 20 μHz. The strength of the source is sufficient to excite globe circling surface waves. We conclude from these observations that volcanoes can excite "harmonic tremors" at much longer periods than previously observed. Our preferred source model involves feedback between local atmospheric oscillations and the eruption process. The physics responsible for this feedback remains subject to speculations.

1. The Seismic Signal from Mt. Pinatubo

We first noticed (in real time!) the low-frequency signal from the Mt. Pinatubo (ϕ = 15°14'N, λ = 120°35'E) eruption in the Philippines in the gravity record of the Black Forest Observatory (BFO) shown in Figure 1. The long-period seismic signal lasts from about 7^{00} to 20^{00} UTC on June 15, 1991. While the Rayleigh wave trains R_3 and R_4 of an earthquake in the South Sandwich Islands region with surface wave magnitude $M_s6.3$ can clearly be identified before the onset of our signal, no earthquake larger than $M_s5.5$ occurred worldwide until 23^{00} UTC. The long lasting envelope suggests that the source radiated energy for at least 8 hours. The same signal was also recorded with several superconducting gravimeters, by the gravimeters of the IDA network (International Deployment of Accelerometers [Agnew *et al.* 1986]) and many of the high quality 3-component VLP stations operated by global networks. Because of the temporal coincidence of this signal with the crisis at Mt. Pinatubo, this volcano was immediately the prime suspect.

36 events with magnitudes less than $M_s5.5$ are listed to have occurred on Luzon Island in this time window, demonstrating the crisis. None of these quakes can be made responsible for the long-period signal we see. The same is true for "silent earthquakes" [Beroza and Jordan, 1990]

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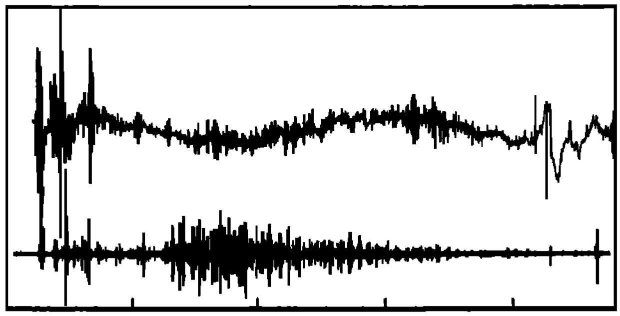

Fig 1. Raw gravity record from BFO (top) showing the low-frequency signal between 7^{00} and 18^{00}. The wave packets at the beginning of the record are Rayleigh waves from the $M_s6.1$ Kaukasus event (0^{59}) and the $M_s6.3$ South Sandwich Island event (1^{13}). R_4 from the second event arrives at 6^{00}. The signal from Pinatubo arrives at 7^{00} and lasts till 20^{00}. A frontal thunderstorm is the cause for the excursion at 21^{00}. Bottom: band-passed VLP-Z recording from KMI. The signal from the Pinatubo eruption is particularly large on this trace due to the small epicentral distance. Both traces exceed the plot limits during the first two hours. The amplitude of the signal at 8^{00} corresponds to 0.3 μgal for BFO and 0.8 μgal for KMI.

since such events which are localized in space and time should produce a very wide spectrum.

Given the diffuse onset of the signal, we cross-correlate 2 hour segments which contain the beginning of the signal to determine the time-lag between the arrivals at different stations. As reference wave form we take the vertical component VLP recording from the CDSN (Chinese Digital Seismograph Network) station KMI which is also shown in Figure 1. This technique produces peaked cross-correlation functions so that the time lag can be unambiguously determined (Figure 2). The linear trend of the lag with epicentral distance shows that the signal travels along the Earth's surface and the small scatter demonstrates that the signal originates near Mt. Pinatubo. The slope of the best fitting line corresponds to a group velocity of 3.78 km/s. Since this velocity is close to the average group velocity of Rayleigh waves with a period of 250s we conclude that the signal propagates as Rayleigh waves. This finding is also confirmed by the particle motion at KMI which lines up with the azimuth of Mt. Pinatubo (Figure 2a). Amplitude spectra from IDA stations and BFO are shown in Figure 3.

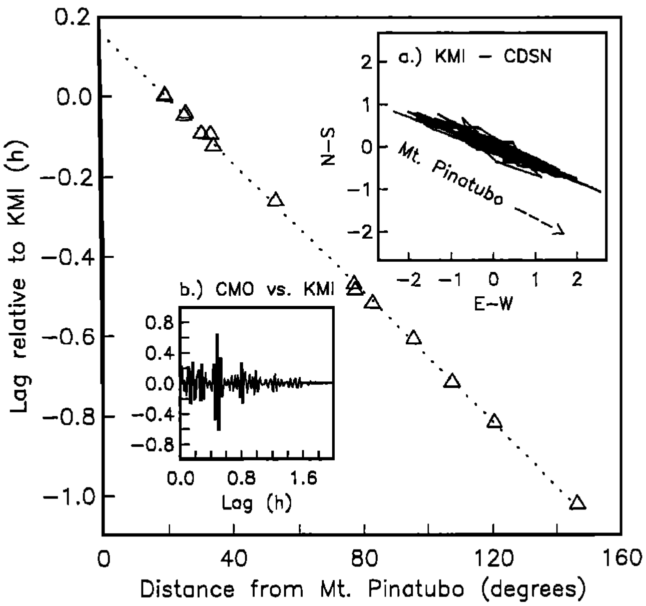

Fig. 2 Time lag vs. distance from Mt. Pinatubo as measured by cross-correlating 2 hour long VLP recordings (6^{00} - 8^{00}). Insert (a): horizontal particle motion (8^{00} - 9^{00}) at KMI. The near parallel alignment of the particle motion with the direction to Mt. Pinatubo is expected for Rayleigh waves. Insert (b): cross-correlogram of CMO and KMI from which a lag of 1750 s was measured.

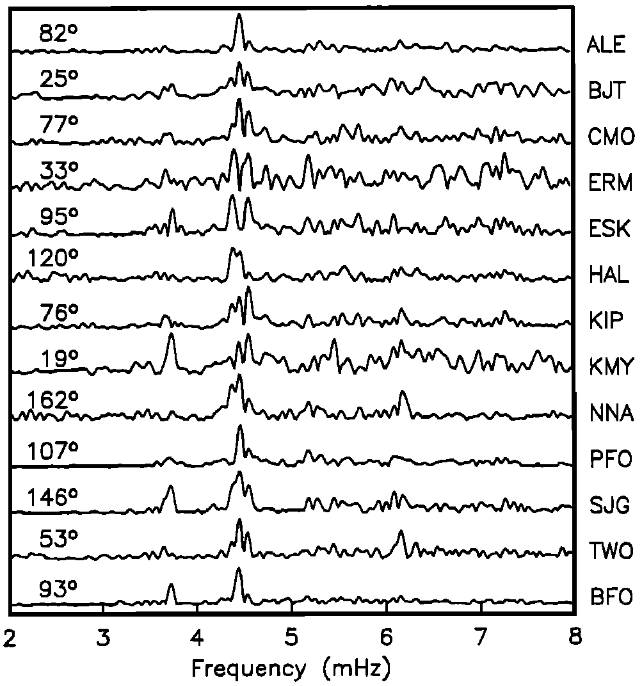

Fig. 3 Linear amplitude spectra for the main eruption of Mt. Pinatubo (6^{00} - 14^{00}). The records are taken from the IDA network and BFO. Two resonances at 3.68 and 4.44 mHz are visible on all spectra. Since the time window contains recurring Rayleigh waves up to at least R_5 we can resolve individual fundamental spheroidal modes, *i.e.* the peaks of the resonance around 4.44 mHz are ${}_0S_{36} - {}_0S_{38}$. The spectra are normalized to have the same maximum amplitude. The epicentral distance of the stations is given at the left margin.

The spectra are bichromatic with resonances at 3.68 and 4.44 mHz visible at all stations.

We studied the phase coherence of each resonance at all stations using a method similar to the "Summation Dial" of Bartels [1938] and find that the source radiates coherently for the entire duration of the signal.

2. Long-period Resonances from other Eruptions

In the hope of finding additional clues to the cause of the narrow band signal we inspected the digital VLP recordings from the most explosive eruptions since 1975. These are the eruptions of Bezymianny (Kamchatka) from February 11, 1979, Mt. St. Helens from May 18, 1980 and El Chichón (Southern Mexico) from April 4, 1982.

The 1979 Bezymianny eruption was too weak to excite either globe circling surface waves or air waves.

The Mt. St. Helens eruption has led to a strong excitation of Rayleigh waves [Kanamori and Given, 1982]. But looking at spectra of 6 hour long records we cannot find any "Pinatubo type" resonances. Obviously, the source of the Rayleigh waves was impulsive rather than harmonic. This conclusion is also confirmed by the studies of *e.g.*, Kanamori *et al.* [1984] who show that most of the seismic energy release occurred within less than 4 minutes.

The El Chichón eruption is the only other occurrence of the low-frequency "Pinatubo type" resonances that we could find thus far. A record section with the IDA data for this event is shown in Figure 4. The main energy release occurs within less than 1 hour so that the Rayleigh waves R_1 and R_2 can be clearly distinguished. Note that this was not the case for Pinatubo. Also visible in Figure 4 is the direct air wave travelling with a group velocity of approximately 300 m/s. Amplitude spectra show two resonances at 3.76

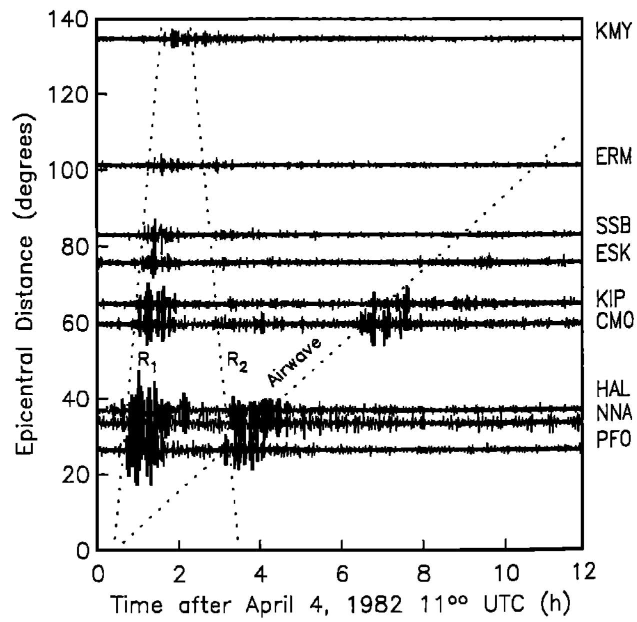

Fig. 4 Record section for the El Chichón eruption. From the envelope of the records near the epicenter we estimate the duration of the main activity to last one hour. The expected arrival times for Rayleigh waves R_1, R_2 and the direct air wave (300 m/s) are indicated with dashed lines.

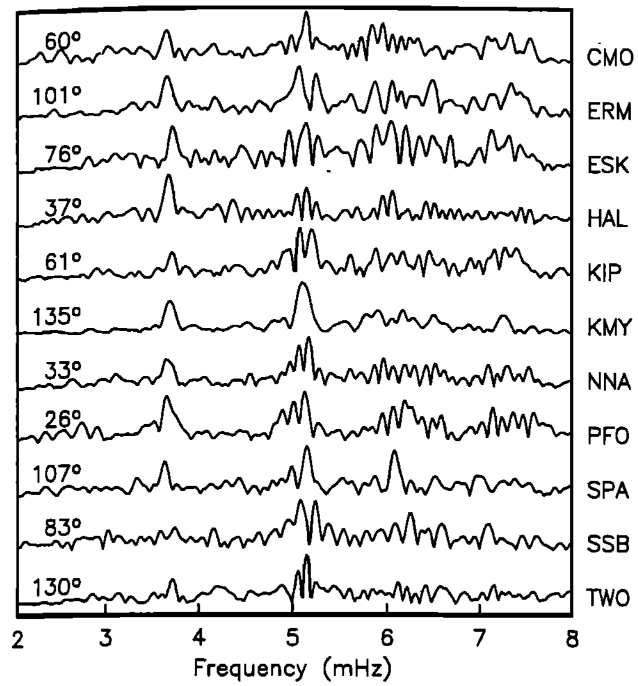

Fig. 5 Amplitude spectra of IDA records from the first six hours shown in Figure 4. The two resonances at 3.76 and 5.14 mHz are clearly visible on all spectra. The spectra are normalized to have the same maximum amplitude.

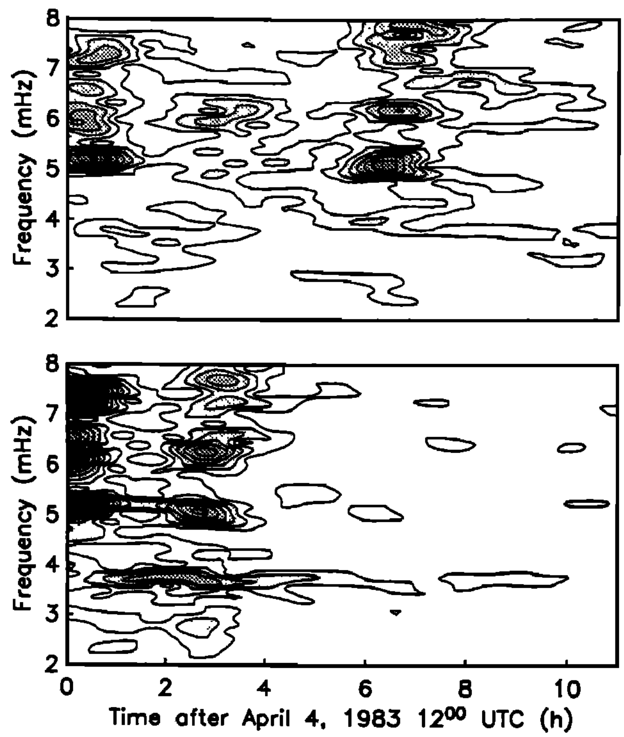

Fig. 6 Sonogram of the records from CMO (top) and PFO (bottom) shown in Figure 4. R_1 arrives in the first hour at both stations and the air wave after 2h at PFO and after 6h at CMO. R_2 arrives after 3h at CMO. At PFO R_2 arrives simultaneously with the air wave but its amplitude is expected to be even smaller than at CMO. Note the similar frequency content of R_1 and the air wave.

and 5.14 mHz (Figure 5). Table 1 summarizes the frequency measurements.

3. Observations of Infrasonic Signals

The eruption of Mt. St. Helens produced a short acoustic signal which was detected on microbarographs worldwide [*e.g.*, Müller and Zürn, 1983]. The spectral content of this signal was very wide, similar to the Rayleigh waves from that same eruption or air waves from atmospheric nuclear explosions [*e.g.*, Harkrider, 1964]. Sonograms for PFO and CMO clearly show that the air wave has the same frequency contents as the Rayleigh wave R_1. (Figure 6)

Atmospheric pressure fluctuations caused by the Mt. Pinatubo eruption have first been observed at a distance of 20 km from the volcano on the microbarogram from Clark Airbase [Kanamori and Mori, 1992]. Since this is an analog paper record with very limited time resolution we cannot perform a spectral analysis on it to see if the atmosphere above Pinatubo oscillated in the same bichromatic fashion as the Rayleigh waves. All one can say from that record is that the amplitude of the signal reached 3 mbar and that the atmosphere reverberated for eight hours. In the far-field we inspected continuous digital microbarograph data from BFO and PFO but we could not find any air wave arrival in these recordings.

Table 1 Estimated resonance frequencies for the Pinatubo and El Chichón Volcanic eruptions. N is the number of individual observations and σ their standard deviation. f is the estimated mean frequency and df is the standard error of f. All units are in μHz. The frequencies were measured from spectra of 3h long time series in order to minimize interference between recurring Rayleigh waves.

eruption	N	f	df	σ
Mt. Pinatubo	17	3680	4	16
	21	4445	4	13
El Chichón	11	3703	13	55
	15	5140	7	44

The recordings of the Mt. St. Helens and the El Chichón eruptions demonstrate that gravimeters and VLP seismometers are sensitive air wave detectors. The difficulty with the Pinatubo eruption is that the long duration of the Rayleigh waves masks the arrival of the air waves and we see only slight evidence for such an arrival at three CDSN stations (KMI, LZH, HIA) and possibly BFO. Considering that the Mt. Pinatubo eruption was explosive much like El Chichón and Mt. St. Helens we expect that it was equally efficient at exciting air waves. Since the air wave also does not show up in sonograms we propose, in analogy with El Chichón, that the air waves from the Pinatubo eruption were bichromatic like the Rayleigh waves.

4. Tentative mechanism for the Source

The observations which a source model has to explain are: (i) Bichromatism, with one frequency practically identical for both eruptions, the other one differing by 0.7 mHz. (ii) The source duration is one hour or more. (iii) For El Chichón air waves have the same frequency contents as Rayleigh waves. For Pinatubo this is only inferred from indirect evidence. (iv) The signal is phase coherent over the full duration of the source.

We present two models which allow to explain the above observations. In the first case the cause for the periodicity of the source lies below the surface. We propose that either the geometry of the feeding system or periodic spatial variation of the concentration of dissolved volatiles in the magma leads to a periodic, bichromatic eruption. If the eruption is bichromatic both Rayleigh and air waves will also have that same frequency contents. This model is of course highly speculative but the important point is, that if the cause for the periodicity lies below the surface, we don't know of any reason why the low-frequency emission spectra of two different volcanoes should be dominated by exactly two lines–not one and not three or more! The observation that one of the two lines of the Pinatubo and El Chichón eruption are identical remains unexplained as well.

In the second model the narrow band characteristic of the source is not a property of the volcano but is imposed by the atmosphere through feedback. To motivate this feedback model we first consider what the signal of a long eruption consisting of a random sequence of individual explosions would look like. Linearity assumed, we expect Rayleigh and air waves with broad frequency contents, similar to the Mt. St. Helens observations. If the Rayleigh waves are excited by local coupling with vertical atmospheric resonances and not by the eruption itself, they may have the observed bichromatic frequency contents (see below). In fact Kanamori and Mori [1992] have shown that the observed 3 mbar pressure signal is sufficient to generate Rayleigh waves matching the observed amplitudes. Observations that speak against a random eruption sequence are the phase coherence of the radiation and the bichromatism of the air waves.

If we introduce feedback, however, and allow the components of the atmospheric pressure field for which the horizontal wave number k vanishes to modulate the eruption dynamics we have a frequency selective mechanism which can lead to both narrow band Rayleigh and air waves. Such a feedback mechanism can also explain the phase coherence of the source and the long-term stability of the resonance frequencies. The rise time of this "oscillator" would have to be much shorter than one hour. The exact physical process by which a 3 mbar pressure signal can control the eruption remains unclear at this stage and must be addressed in further studies. The reason for allowing only those components of the pressure field for which $k = 0$ to participate in the feedback is that all other modes rapidly propagate away from the source region. Harkrider [1964] has computed the transfer function for a reference atmospheric model and finds that between 2 and 8 mHz and for $k = 0$ the atmosphere has two distinct resonances, both of which are near 4 mHz. The lower resonance is the fundamental gravitational and the higher one the fundamental acoustic mode. With the two resonances identified in this way we suggest that the frequency of the lower resonance is essentially the same for both eruptions since the gravitational mode depends on the scale height of the atmosphere. The frequency of the acoustic mode differs because acoustic modes are sensitive to the temperature profile in the atmosphere which varies more with latitude and season than the scale height.

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