Infrasonic Signals Associated with the Aftershocks of LuShan Earthquake of April 20th, 2013

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ABSTRACT

On April 20th, 2013, a strong earthquake (Ms 7.0, depth of 13 km) occurred in LuShan County, Southwestern Sichuan province, China, followed by a series of aftershocks (Ms = 3.0~5.4). Infrasonic waves associated with the earthquake were detected and recorded by a digital infrasound recording system in our lab located in Chengdu city. Fourier analysis was used to determine the amplitude and frequency characteristics of each infrasonic recording. A certain frequency distribution range was clearly identified in the spectrograms of all analyzed shocks. Furthermore, a logarithm regression relation is also found between aftershock magnitude and peak value of corresponding infrasound events in amplitude spectra based on analysis results of more than 30 observed events. This study presents a data set and an empirical relationship. This relationship requires additional testing with observations from other earthquake aftershock sequences. These results improve our understanding of local infrasound produced by the coupling of earth surface motion to the atmosphere.

Keywords: frequency characteristics, spectrogram, local infrasound, LuShan earthquake

1. INTRODUCTION

Infrasound signals generated by natural and man-made sources are composed of low frequency acoustic waves with frequencies ranging from 0.01Hz to 10Hz. It is well known that infrasound waves can be generated by earthquakes through several mechanisms, e.g., [1-3]. The development of cracks in the crust of the Earth is accompanied by a generation of seismic waves, which causes elastic motions of ground surface. These ground motions cause the radiation of infrasonic waves, which transport energy up through the atmosphere [4]. Infrasound produced by earthquakes may be classified into local and epicentral sources as well as from geographical areas diffracting these signals, e.g., [1, 3, 5]. Local infrasound signals are generated at the infrasound station when seismic waves couple to the atmosphere [1, 3]. Epicentral infrasound which can be observed at a far-away station arises from the strong ground motions in the
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epicentral area. The infrasound is then propagated through the atmosphere to the infrasonic station at a mean signal speed of about 300 m/s, and travels through the station area [1, 6-8]. Diffracted infrasound is associated with the passage of seismic surface waves through an area of extreme topography such as mountains or cliffs [2, 8, 9].

At 8:02:46 am on April 20, 2013 (Beijing Time is 8 hours ahead of GMT), a great earthquake measuring Ms 7.0 and a series of aftershocks struck Lushan County of Sichuan Province in the Southwest of China, which lasted for about 30 s [10, 11]. As shown in Fig. 1, the epicenter was located at 30.284°N, 102.956°E with a hypo-central depth of 12.3 km [12]. These events resulted from the rupture of the Shuangshi-Dachuan fault, southwestern segment of the Jiangyou-Guanxian fault [13]. This great earthquake and the associated aftershocks were sources of local and epicentral infrasound signals observed at one digital infrasound recording system in the State Key Laboratory of Geohazard Prevention and Geoenvironment Protection (SKLGP), China. The epicenter of the earthquake lay about 130 km southwest of the infrasonic recording system location.

Mutschlechner and Whitaker [7] have shown that the logarithmic relationship between normalized amplitude of infrasound and seismic magnitude since magnitude is related to ground motion strength which, in turn, drives the infrasound generation. Arrowsmith et al. [5] reported and studied the infrasound observations from the Circleville earthquake, which occurred on January 3\textsuperscript{rd}, 2011. However, more attention was paid to the atmospheric signals from the epicenter region rather than the local infrasound in their studies. The purpose of this paper is to present the observations of the local infrasound signals from the Lushan earthquake and its associated aftershocks via one recording station at a fixed observing distance. Even the infrasound events produced by events of small magnitudes down to Ms 3.0 were detected in this study. The characteristic frequencies of the infrasound signals are found through a spectrogram analysis method. Using a statistical regression analysis

![Figure 1](image-url)

**Figure 1.** The epicenter location of the Lushan earthquake on April 20\textsuperscript{th}, 2013. SKLGP indicates the location of the infrasonic recording system.
method, based on more than 30 recorded infrasonic events associated with the aftershocks, an empirical relationship between the shocks’ magnitudes and peak values in the amplitude spectra of the respective infrasonic waves is derived.

2. OBSERVATIONS

Figure 1 shows the location of the epicenter of this earthquake along with the Shuangshi-Dachuan fault. A digital infrasonic recording system was installed and tested in SKLGP. It is composed of a capacitive type infrasonic sensor InSAS2008 [14], which is developed by the Institute of Acoustics at the Chinese Academy of Science in China, and a digital Data Acquisition System (DAS) with embedded data storage card. Figure 2 shows the schematic view of the infrasonic sensor. It is mainly made up of an air passage, a front cavity, a diaphragm, a plate, a pressure balance passage and a back cavity. The plate and the diaphragm constitute a parallel plate capacitor, whose capacity is $C_0$. The vibration of the diaphragm makes a capacitance change with $\Delta C$ under acoustic pressure effect. In this sensor, the diaphragm is a nickel foil with thickness of 3~5μm. The distance ($d$) between the plate and the diaphragm is about 50μm. The role of the pressure balance passage is to balance the static pressure between the front cavity and the back cavity to keep the diaphragm’s sensitivity from being affected by the additional force induced by real ambient pressure oscillation. In general, the essential principle of the sensor is that the capacitance change, caused by acoustic pressure fluctuations, is modulated to voltage output [15]. The output of capacitive infrasonic sensor is proportional to the average displacement of the diaphragm, rather than to the oscillation amplitude of the diaphragm [16]. Therefore, the sensor should be sensitive to atmospheric pressure change rather than mechanical shaking as induced by seismic waves due to its design principle. More details about the working principle of the sensor can be found in reference [17]. This sensor has a flat and wide frequency response from 0.0001Hz to 100Hz, covering the infrasonic frequency band of interest [14]. The output of the sensor was filtered between 0.01Hz and 20Hz by the digital DAS and is digitized at 100 samples/second. In attempting to test and evaluate the characteristics of the infrasonic signals, the time-frequency spectrum was calculated utilizing the ‘spectrogram’ code of the MATLAB environment [18].
2.1. Infrasonic events associated with the main shock

The Lushan earthquake occurred at the time of 08:02:46 am on April 20th, 2013, as was reported by the Sichuan Earthquake Information Network [11, 13]. Figure 3 shows the observed infrasonic wave from 08:00:00 am to 08:13:20 am on April 20, 2013. E1 (location: 30.3N, 103.0E, depth: 13 km) indicates the first infrasonic event. Unfortunately, E1 is clipped for ~80 s ($\Delta t$) due to the limitation of digitizing of the infrasonic recording system. In the time domain, the peak-to-peak amplitude of the local infrasound event (E1) reached at least 3 Pa, and the duration of the event lasted more than 100 seconds. There is a 6 second delay between the first arrival time and the moment of the large quake due to the detection distance and the error of the system clock. E2 (location: 30.2N, 102.9E, depth: 10 km) and E3 (location: 30.3N, 102.9E, depth: 10 km) can also be identified because two aftershocks occurred at the same time according to the official report by the China Earthquake Administration. Since the velocity of infrasonic waves propagating in the atmosphere is about three hundred meters per second, the three infrasonic events (E1, E2 and E3) are probably the local infrasound, produced by coupling of seismic waves and the atmosphere.

E4 is probably the epicenter infrasound event, which was produced by the main shock, because the duration between E4’s arrival and E1’s arrival is about 400 seconds, which is in accordance with the travel time of epicentral infrasonic waves over the detection distance. Meanwhile, there were no aftershocks or other sources occurring at the same time according to the official report by the China Earthquake Administration. The local infrasound events and the epicenter infrasound generated by the main shock are also further analyzed by calculating the Fourier spectra.

Figure 4 shows the analysis results of the epicentral infrasonic signal produced by the main shock of the Lushan earthquake. In order to derive the time-frequency distribution of the observed signals, a two-dimensional Short-Time-Fourier-Transform (STFT) was applied to the data.

![Figure 3. Infrasonic events observed at SKLG P between 8:00:00 and 8:13:20 local time on April 20th, 2013. E1 occurred at 8:02:52, E2 occurred at 8:06:45, E3 occurred at 8:07:42, and E4 occurred at about 8:09:35. Note that the record of main event (E1) was clipped.](image-url)
The infrasonic event induced by the main shock can be clearly identified in the corresponding time-frequency spectrogram. In Fig. 4 (a), we show the single-sided amplitude spectrum of the epicentral infrasonic event (E4 in Fig. 3). The frequency content of this epicentral infrasound is mainly in the range of less than 1.6 Hz and the peak value is about 0.9 Hz.

2.2. Infrasound associated with aftershocks
After the main quake, more than 30 local infrasonic events, associated with aftershocks with magnitude \( M_{s} \geq 3.0 \), were detected and recorded by the infrasound recording system. All of the recorded infrasound events were identified according to the time of occurrence of the respective aftershocks and analyzed with the aid of the ‘spectrogram’ method in the environment of MATLAB. Figure 5 shows part of some infrasound events and their analysis results. The dominant frequency distribution of each infrasonic event can be identified clearly in the spectrogram and single-sided amplitude spectrum. Figure 6 shows the distribution of characteristic frequencies of 32 infrasonic events generated by the LuShan earthquake and its aftershocks. Figure 7 shows the distribution characteristics of the dominant frequencies of the observed infrasonic events based on the bootstrap method [19] (resample count = 1000).

2.3. Estimation of the relationship between infrasound signal and surface magnitude
The vertical component of the ground surface motion due to a seismic wave causes the local infrasound [1]. It is anticipated that there is a relation between the peak value in the single-sided amplitude spectrum (\( MA \)) and the seismic surface magnitude (\( M_s \)). Earthquake magnitude is related to ground motion strength which, in turn, drives the infrasound event generation. All analysis results enable us to evaluate the correlation between \( M_s \) and the \( MA \). In Fig. 8, the magnitude \( M_s \) is plotted versus \( \log(MA) \). The least squares fit to these data is
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Figure 5. Characteristics of some local infrasound events generated by aftershocks occurring between April 20 and April 21. Time mark indicates the start time of the x (Time) axis respectively.
The fitting relationship suggests that the intensity of a coherent infrasound event is mainly determined by the magnitude of the respective ground motion shock generating the seismic surface waves.

To quantify the goodness-of-fit between the surface magnitude of shocks and the peak value in the amplitude spectra of the associated infrasonic events, a bootstrap analysis is performed for estimating uncertainties of the analysis [19]. Figure 9 shows an estimation of the variation of the correlation coefficient across all the

\[ Ms = 0.56 \log(\text{MA}) + 1.6. \]
bootstrap samples (resample count = 1000). The estimation results ($\mu = 0.93, \sigma = 0.02$) indicates that the relationship between $Ms$ and $\log(\text{MA})$ is not accidental but credible.

3. DISCUSSION AND CONCLUSION
This paper presents the analysis of infrasound generated by the main shock and more than 30 aftershocks of the Lushan earthquake on April 20th, 2013. The focus of the paper is on the amplitude and frequency characteristics of the aftershock signals.

The corresponding infrasonic events of the aftershocks were also investigated one by one by analyzing the individual time-frequency distributions and relating the events to the time of occurrence of the earthquakes. Specifically, the average
frequency of the power spectra is found to be about 3.87 Hz. However, local infrasound generated by the aftershocks has higher dominant frequencies than the epicentral infrasonic signal produced by the main shock. Unfortunately, the local infrasound associated with the Lushan main shock has not been analyzed in depth because the clipping problem may alter the frequency content of the signal in complex ways, which are not clear to us at present. Generally, the frequency distribution of local infrasound is in range of ~3.6-4.2 Hz, and the epicentral infrasonic signal is mainly distributed within the low frequency range (<1.5 Hz).

In addition, the maximum infrasound amplitude (MA) versus surface magnitude (MS) is analyzed and a “log-linear” relationship is empirically derived with a high correlation coefficient in explaining the observation. A similar relation has been found between normalized amplitude and local seismic magnitude (ML) by Mutschlecner and Whitaker [7] who have conducted studies composed of events from every season and the infrasonic signals potentially being influenced by the prevailing wind directions, which are a function of season. This relation is of a large variance because of the effect of the variance of surface motion as a function of magnitude and the inherent uncertainties in the stratospheric winds [7]. So, a quantitative comparison between the relationship in reference [7] and our study is difficult to achieve due to the different parameters and the different signal properties. However, both relations indicate that infrasound characteristics associated with earthquakes are determined by the earthquakes’ magnitudes. The ground shaking during an earthquake is caused by a fault slip [13], and this vertical ground motion can produce infrasound [1, 20]. So, there is an indirect relationship between fault slip and infrasound. This relationship tells us that infrasound correlates with local seismic waves during an earthquake because the seismic waves generate the observed acoustic signal by perturbing the air at the receiver [3]. Analyzing and understanding the characteristics of infrasound generated by the Lushan earthquake should provide an opportunity for further earthquake research.

With the aim to study earthquake and co-seismic geo-disasters, the authors will develop an infrasound monitoring array and combine the infrasound detecting technique with other advanced scientific methods in our ongoing research based on the current results. It is hoped that a study combining the infrasound observations with coherent seismic measurements will allow a better understanding of the physical mechanism for earthquake associated infrasonic wave generation.

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