Hilbert-Huang transform of infrasound for tsunami early warning systems

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Abstract. When an earthquake occurs tectonically and volcanically, it is preceded by the emergence of sound wave propagation that cannot be heard by the human ear because it has a low frequency, called infrasound. These infrasound waves are difficult to detect because they are much weaker than earthquake waves and other natural sound waves in nature. The Hilbert-Huang transform method (HHT) is proposed, which in principle decomposes a wave into several simpler sinusoidal harmonic waves so as to separate the low-frequency infrasound waves from the other waves. Once separated, the envelope frequency can be determined which represents the frequency of the earthquake occurrence, then the amplitude represents the predicted earthquake strength, and the wave propagation phase that represents the location of the earthquake source. From the comparison of secondary data, it was obtained that HHT was able to obtain all three information faster than the data from seismographs so that it had the potential to increase the evacuation time which in turn reduced the potential for greater casualties and losses.

1. Introduction
A tsunami is a natural disaster in the form of destructive ocean waves, they can reach tens of meters in height and have speeds of up to tens of kilometers per hour when they reach land. According to WHO [1] between 1998-2017, a total of 250 thousand victims were caused by the tsunami disaster, of which 227 thousand or nearly 91% came from the tsunami disaster in Aceh in 2004. The tsunami early warning system used by the Indonesian Meteorology, Climatology and Geophysics Agency (BMKG) consists of two systems, which is a monitoring system on land and a monitoring system at sea. The monitoring system on land uses broadband seismometer technology and a global positioning system (GPS), while the monitoring system at sea uses tide gauges and tsunami buoys [2]. It is estimated that the system can provide a tsunami warning within a maximum period of 20 minutes after the earthquake occurs. However, during the tsunami that occurred on 22 December 2018 in the Sunda Strait, BMKG did not issue a warning. This system can only issue an early warning on tsunami caused by earthquakes, while the tsunami in the Sunda Strait was caused by landslides due to the volcanic activity of Mount Anak Krakatau [3]. The characteristics of the waves of volcanic activity that propagate as an early indicator of a tsunami have different properties compared to general tectonic earthquake waves, which is a wave at low frequencies called infrasound.

Infrasound is a sound wave that has a frequency below 20 Hz and travels at a speed of about 340 m/s in the atmosphere. The infrasound signal was successfully detected when Mount Anak Krakatau erupted, but before the tsunami occurred [4], [5] also explained that before an earthquake with a magnitude above 7, infrasound signals could be detected up to one week before the earthquake occurred. Infrasound can also be generated by the tsunami as described by [6], [7] explained that the amplitude of the infrasound signal can be used to determine the magnitude or estimate of the strength of the
earthquake that occurred. The frequency of infrasound describes the frequency of occurrence and the speed of propagation of vibrations at the source, and from the derivative of the frequency against time, the phase of the infrasound wave will be obtained which represents the direction of arrival or the location of the source [8]. The main problem is getting the three characteristics of the amplitude, frequency, and phase of the infrasound wave which is "immersed" by other waves such as footsteps, animal sounds, etc. which have a greater loudness.

The common methods used to obtain the infrasound characteristics are spectrogram to determine the characteristics in the form of frequency and amplitude and Progressive Multi-Channel Correlation (PMCC) to determine the frequency characteristics, speed of propagation, and direction of arrival of infrasound waves. Although these two methods are commonly used, both methods still have some weaknesses. The spectrogram method has the disadvantage of the inaccuracy of the frequency obtained if the information about time is obtained correctly and vice versa, or what is called the Heisenberg uncertainty principle. The PMCC method also has disadvantages which are susceptible to background noise at each infrasound measurement station, so it requires several parameters to be set for optimal results [9]. In this paper, it is proposed to use the Hilbert-Huang Transform (HHT) to answer the weaknesses in the two previous methods and to obtain the characteristics of infrasound waves.

Hilbert-Huang transform (HHT) is a method that can process non-linear and non-stationary signals. The first step is called the Empirical Mode Decomposition (EMD). It simply looks for the components of some basic (decomposition) sine waves which when added together will produce the original wave called Intrinsic Mode Function (IMF). The second step is the Hilbert Spectral Analysis (HSA), where some of the unraveled sine waves are converted (transformed) into analytical waves in the form of frequency, amplitude, phase, time [10]. From these several basic sine waves, only those with a frequency below 20 Hz are selected, thereby eliminating the constituent components with higher frequencies (filtering). The advantages of HHT are that it can act as a filter frequency greater than 20 Hz and noise cancellation and its adaptive nature depend on the signal being processed [11]. The algorithm is simpler than PMCC so it is computationally faster without reducing accuracy so that it has the potential to be applied to tsunami early detection systems originating from volcanic and tectonic activity.

This paper will explain infrasound and its advantages and problems, continued by the explanation of the role of the HHT method to solve the problem of using infrasound as a tsunami early detection followed by simulations.

2. Review

2.1. Infrasound

Infrasound is a sound wave that has a frequency below the threshold of human hearing frequency (<20 Hz) and can propagate up to thousands of kilometers. Infrasound sources from nature such as volcanic eruption [12], earthquakes [13], [6], tsunamis [14-15]. This paper only focused on infrasound waves generated by the earthquake as a suggestion for improving the performance of the tsunami early detection system.

Research on infrasound waves generated by earthquakes has been widely carried out, but one of the facts of infrasound waves related to earthquakes was discovered by [5]. The study found that, before an earthquake with a magnitude above 7, unusual (abnormal) infrasound waves were detected up to one week before the earthquake occurred. This study used a case example from the 2004 earthquake in Aceh. The result is that one week before the earthquake in Aceh, unusual infrasound waves can be seen at the same source position as the epicenter. This fact explains that infrasound waves can be an alternative if they are used for the early detection of earthquakes that have the potential to generate tsunamis. Another fact is that tsunamis can also produce infrasound waves due to the interaction between ocean waves and the atmosphere [14]. This fact can support the use of infrasound waves for the early detection of tsunamis because the propagation of infrasound waves is faster than tsunamis [15].

When using infrasound waves for the early detection of tsunamis, it is necessary to know the characteristics of the infrasound waves in order to avoid false warnings. Table 1 summarizes the various characteristics in the form of amplitude and frequency of infrasound waves, especially those generated by the earthquake and tsunami from several research results. Table 1 shows that the amplitude of the infrasound wave is relatively small because it is only in the range of 0.2-2 Pa, this amplitude is very
susceptible to being covered by waves of even higher amplitude. Therefore, it is one of the main problems that must be solved to use infrasound waves as early detection.

| Source of infrasound wave          | Amplitude | Frequency   |
|------------------------------------|-----------|-------------|
| Mount Anak Krakatau [4]            | 0.9 Pa    | 0.5-5 Hz    |
| 2004 Aceh earthquake [14]          | 0.5 Pa    | 0.05-0.1 Hz |
| Tsunami [14]                       | 1 Pa      | 0.02-0.15 Hz|
| 2018 Palu earthquake [6]           | 0.3 Pa    | 0.05-4.4 Hz |
| 2016 Italy earthquake [13]         | ~2 Pa     | 0.4 Hz      |
| Microbaroms [12]                   | 0.2 Pa    | 0.2 Hz      |

2.2. Signal processing

The methods used to solve the problem of finding the characteristics of infrasound waves vary, several of them will be described. Table 2 summarizes the comparison between the infrasound signal processing methods using the spectrogram, PMCC, and HHT from the existing studies.

| Processing Method | Frequency-amplitude | Direction of arrival |
|-------------------|---------------------|----------------------|
| Spectrogram       | Yes                 | No                   |
| PMCC              | Yes (frequency only)| Yes                  |
| HHT               | Yes                 | Yes                  |

2.2.1. Spectrogram

A spectrogram is a method for obtaining the information about time and frequency at the time infrasound waves occur as explained in [4]. In principle, the spectrogram is the placement of the wave frequency obtained from the square of the amplitude of the frequency obtained using the Fourier transform (vertical axis, Hz) concerning time (horizontal axis). This method has disadvantages. First, the imprecision of the frequency obtained if the information about time is obtained correctly and vice versa, or what is called the Heisenberg uncertainty principle. Second, the frequency obtained is very susceptible to being disturbed by waves that are not infrasound waves, so it requires measuring instruments that have high sensitivity.

2.2.2. PMCC

The method of processing infrasound data to get the speed of propagation and direction of the infrasound waves is PMCC (Progressive Multi-Channel Correlation), [16] PMCC works based on the inter-station correlation function which has a set of sensors (array), where the sensors will have a time-delay for each seismic or infrasound waves that occur, which will be used to locate the seismic or infrasound source. The disadvantages of the PMCC method are first, in looking for the characteristics of the infrasound waves, this method uses the time delay for each sensor by cross-correlation method. However, the time delay obtained has shortcomings in terms of accuracy, due to the absence of a distinction between the infrasound signal and signals from other sources [17]. Second, the use of the PMCC method is very dependent on the background noise level of the sensor, this makes the method very dependent on several parameters that must be adjusted to get optimal results [9].
2.2.3. Hilbert-Huang transform

Another method that can be used is the Hilbert-Huang transform (HHT). Hilbert-Huang transforms only aims to determine the characteristics of infrasound based on the frequency, amplitude, and direction of arrival (based on phase). This method consists of Empirical Mode Decomposition (EMD) and Spectra Hilbert Analysis (HSA) [11]. In this research, we use simulations to show the performance of the HHT method using secondary data. Empirical Mode Decomposition (EMD) simply looks for components of several basic (decomposition) sine waves which when added together will produce the original wave called Intrinsic Mode Function (IMF) [11].

Hilbert Spectral Analysis (HSA) is used to determine the characteristics of infrasound waves in the form of frequency, amplitude, and phase (can be reduced to the direction of arrival of infrasound) [11]. The principle of HSA is to use the Hilbert transform to find peaks in signal (envelope) which will be represented in the form of an analytical signal (a signal that has real and imaginary components). The mathematical form of the Hilbert transform is given by,

\[
y(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} \, d\tau
\]

where \(x(t)\) is the original signal (infrasound) and \(y(t)\) is the result of Hilbert transform. After obtaining \(x(t)\) and \(y(t)\), the two results are formed into the analytical signal as follows,

\[
z(t) = x(t) + iy(t) = a(t)e^{i\theta(t)}
\]

\(z(t)\) is an analytical signal that has real \((x(t))\) and imaginary \((y(t))\) components. From \(z(t)\) we can determine the instantaneous amplitude (amplitude that changes with time) and the instantaneous phase (the phase that changes with time) as follows,

\[
a(t) = \sqrt{x^2 + y^2}, \quad \theta(t) = \tan^{-1} \frac{y}{x}
\]

where \(a(t)\) is the instantaneous amplitude and \(\theta(t)\) is the instantaneous phase. From this phase, it can be reduced to the direction of propagation of the infrasound waves. Moreover, from the phase, we can also get the frequency characteristics of the infrasound wave using the equation as follows,

\[
\omega = \frac{1}{2\pi} \frac{d\theta}{dt}
\]

where \(\omega\) is the instantaneous frequency in units of Hz [11].
3. Method
In supporting this review, simulations with the HHT method were carried out using the MATLAB 2020 software. The infrasound data used is data from the earthquake at Palu in September 2018 that we got from the IRIS website (http://ds.iris.edu/wilber3/). The results of this simulation are an image in the form of time-frequency, which will then be compared with the results of existing research.

4. Result
The result of EMD can be seen in Figure 3, this figure is a decomposition of the infrasound signal generated by the earthquake in Palu in September 2018. The vertical axis is the amplitude in Pascal units and the horizontal axis represents the time in seconds. Based on Figure 3, it can be seen that the infrasound signal has a high-frequency component (Figure 3c) to a low-frequency component (Figure 3d). The components of this signal will be sorted so that signals other than infrasound can be removed (filtering) [10]. By using IMF data in the EMD section, the HSA results on the infrasound signal can be seen in Figure 4, the dotted line shows when infrasound has the highest energy or amplitude. The characteristics obtained from HSA in Figure 4 are the frequency when the maximum energy is between 0.1-2 Hz. If we compare these results with the results from [9] which use the same data but different methods namely PMCC, it is found that the frequency range that has the highest energies are more focused using the HHT method compared to PMCC, but it has not been used to determine the direction of arrival of infrasound signals.

Figure 2. EMD simulation results; a) original infrasound signal, b) first IMF, c) second IMF, d) seventh IMF.

Figure 3. HSA simulation results on the infrasound signal.
In determining the direction of arrival of the infrasound signal using the HHT method, [18] used the time delay from the decomposed signal (EMD) to several components (IMF) in the radar system. From the IMF, a delay time is sought for each sensor which is then used to determine the direction of the source signal. The result is the accuracy of the direction of arrival in the form of an increased angle rather than using the original signal. This can happen because the IMF has less noise (interference) than the original signal. These results explain that HHT has the potential to know the direction of the source signal.

5. Conclusion
It can be concluded that the use of infrasound as a technology for the early detection of tsunamis is very potential. However, the main problem with applying infrasound as early detection is looking for the characteristics of the infrasound signal that can be "immersed" by other signals. The solution for this problem is to use a signal processing method. HHT has the potential to be used as a method in infrasound signal processing, because of the several advantages as described in the previous chapter with simulations (Figure 3 and Figure 4) compared to PMCC and spectrograms. Meanwhile, to determine the direction of arrival of infrasound waves, the HHT method has great potential even though its application is still in radar systems.

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