

Research Article

Estimation on the Underwater Explosion Equivalent Based on the Threshold Monitoring Technique

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Underwater nuclear explosions can be monitored in near real-time by the hydroacoustic network of the International Monitoring System (IMS) established by the Comprehensive Nuclear-Test-Ban Treaty (CTBT), which could also be used to monitor underground and atmospheric nuclear explosions. The equivalent is an important parameter for the nuclear explosions' monitoring. The traditional equivalent estimation method is to calculate the bubble pulsation period, which is difficult to obtain satisfactory results under the current conditions. In this paper, based on the passive sonar equation and the conversion process of acoustic energy parameters in the hydroacoustic station, the threshold monitoring technique used for underwater explosion equivalent estimation was studied, which was not limited to the measurement conditions and calculation results of the bubble pulsation period. Through the analysis of practical monitoring data, estimation on the underwater explosion equivalent based on the threshold monitoring technique was verified to be able to reach the accuracy upper boundary of current methods and expand the measurement range to further ocean space, along with the real-time monitoring capability of IMS hydroacoustic stations which could be estimated by this method.

1. Introduction

The Comprehensive Nuclear-Test-Ban Treaty was adopted by the United Nations General Assembly on 10 September 1996 [1]. The purpose of the CTBT is to prohibit all States Parties from carrying out any form of nuclear weapon test explosion or any other nuclear explosions, which is of great significance to promote the comprehensive prevention of the proliferation of nuclear weapons in all its aspects, to the process of nuclear disarmament, and therefore to the enhancement of international peace and security. In order to effectively monitor nuclear explosion activities around the world, the International Monitoring System (IMS) was established according to the CTBT. IMS comprises facilities for seismological monitoring, radionuclide monitoring, infrasound monitoring, and hydroacoustic monitoring to continuously monitor the default events all over the world. IMS hydroacoustic monitoring network is composed of 11

hydroacoustic stations, including 6 hydrophone (H-phase) stations and 5 T-phase (seismic) stations. These stations are designed to monitor the oceans all over the world and detect signals that might originate from any underwater nuclear test [2]. These deep sound channel hydrophones could be used to detect and locate underwater explosions with long distance [3]. Therefore, the location and equivalent estimation are the study emphases within the underwater explosion monitoring field.

As we all know, underwater explosions could produce gas bubbles. The expansion and contraction of gas bubbles could induce a series of bubble pulses: the first one comes from the explosion, the second one comes from bubble collapse, the third one comes from the expansion again, and so on. There are many studies on the measurement of bubble pulsation. Slifko [4] studied the characteristics of deep-water explosion through a large number of marine experiments, and the relationship between the characteristic parameters

of bubble pulsating pressure and water depth and distance was obtained. Chapman [5] measured the properties of shallow underwater explosions, and semiempirical relationships were derived from the data for the properties of both the shock wave and the bubble pulse series. Kun et al. [6] conducted some small-scale charges exploded under different simulated deep-water environments, and the images of the bubble oscillation process were obtained. Liang et al. [7] simulated the spherical explosives in water with different depths by Autodyn, and the pressure attenuation process of the shock wave and the bubble pulsation periods were obtained through simulation. According to the previous studies, the relationship between the underwater explosion depth and bubble pulsation period, as well as the radius can be determined, and the relationship between bubble energy and equivalent can also be reflected from the side. As these studies have shown, there is a semiempirical relationship between the bubble pulsation period, explosion equivalent, and depth. If two parameters were known, then the third parameter can be obtained [8]. However, this method cannot estimate both explosion equivalent and depth of the unknown underwater explosion at the same time. Prior and Brown [9] introduced a method to estimate the order of magnitude of the energy equivalent and detonation depth of underwater explosions based on the acoustical signals radiated. This method determined the ratio of the periods of the first two pulsations made by the gas bubble and formed by an underwater explosion, with bubble pulsation periods being extracted from cepstral of signals recorded on hydrophones. The high deviation of this estimation method is due to the extreme sensitivity of the two bubble period measurements and can only be used to estimate the magnitude of explosion depth and energy equivalent. Moreover, this method can only be applied between the upper limit of the reliable bubble formation and the lower limit of the buoyancy effect on the second bubble pulsation period.

In this article, based on the passive sonar equation and starting with the sound source level of the underwater explosion, a new method to estimate the equivalent of underwater explosions, combining the threshold monitoring technology and conversion process of acoustic energy parameters, which is not limited to the measurement conditions and calculation results of the bubble pulsation period, is as follows.

2. Methods

2.1. Passive Sonar Function of the IMS Hydrophone Station. Sonar system is widely used to detect, identify, locate, navigate, and communicate from underwater acoustic information. According to the working mode of the sonar, it is usually divided into active sonar and passive sonar. IMS hydrophone stations are all passive sonar. Figure 1 shows the information flow diagram of the passive sonar. Different from the active sonar, passive sonar has no transmitting system and detects underwater targets and their state by receiving the radiated noise of the target. There are three

basic links in the information flow of the passive sonar, including sound source, seawater channel, and hydrophone array. In each link, some sonar parameters are needed to describe its characteristics. Sonar parameters include source level SL , transmission loss TL , target strength TS , ocean environment noise level NL , receiving directivity index DI , and detection threshold DT . According to the flow of Figure 1, the sonar equation can be obtained by organically combining the sonar parameters. If the difference between the received signal level and the background noise level is great than or equal to the detection threshold, then the target can be detected by the sonar system. On the contrary, if the difference between the received signal level and the background noise level is less than the detection threshold, then the target cannot be detected by the sonar system. As shown in Figure 2, passive sonar equation (1) includes SL , TL , NL , DI , and DT , simpler than the active sonar equation.

$$SL - TL - (NL - DI) = DT. \quad (1)$$

2.2. Acoustic Model of the Underwater Explosion and Conversion of Acoustic Energy Parameters. IMS hydroacoustic station is mainly used to monitor the underwater nuclear explosion. Taking the underwater explosion as the sound source, the noise produced by the explosion can be obtained by using the principle of explosion similarity. The acoustic model can be obtained by the simulation test, including the maximum pressure and acoustic energy spectrum of the underwater explosion. The function of the maximum pressure of the underwater explosion was synthesized by Swisdak of NSWC through a large number of experimental data of the underwater explosion [10].

$$P_m = K \cdot \left(\frac{W^{1/3}}{R} \right)^\alpha, MP_a, \quad (2)$$

where P_m is the peak pressure of the underwater shock wave, unit is MPa, W is the charge quantity, unit is kg, and R is the distance from the underwater explosion source, unit is m. For the TNT explosive, normally, $K = 52.4$ and $\alpha = 1.13$.

The main parameter of underwater sound energy is generally the sound source level, which needs to be converted into mechanical parameters in mechanical calculation. According to the definition formula of the sound source level, the pressure at 1 m away from the center of the sound source is

$$P = 10^{(SL/20)-6}, P_a. \quad (3)$$

According to formula (2), the equivalent of the spherical charge can be obtained by the following equation:

$$W = \left[\left(\frac{P_m}{K} \right)^{1/\alpha} R \right]^3. \quad (4)$$

Considering equations (3) and (4) and assuming $R = 1$ m and the peak pressure $P_m = P$, the relationship between the peak pressure of the underwater explosion

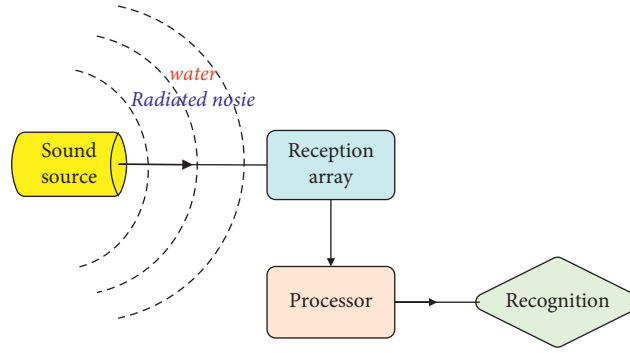


FIGURE 1: Information flow of the passive sonar.

shock wave and the sound source level is established. Substituting equation (3) into equation (4), the equivalent of the spherical charge can be calculated as the following equation:

$$W = \left[\frac{10^{(SL/20)-6}}{K \times 10^6} \right]^{3/\alpha} = \left[\frac{10^{(SL/20)-12}}{K} \right]^{3/\alpha}. \quad (5)$$

2.3. Threshold Monitoring Technology. Threshold monitoring (TM) technology is a method proposed by NORSAR in 1989 to evaluate the monitoring capability of the seismic network by using real-time seismic data [11, 12]. It has been applied to the International Data Center of CTBT and established the TM system. This section will explore the TM method of estimating the equivalent underwater explosion.

For hydrophone stations, assuming that the estimated value of the sound source level of the received signal is SL , the equivalent-estimated W of the underwater explosion can be obtained from equation (5), called \hat{W} . According to statistics, equivalent-estimated value \hat{W} can be considered as the following normal distribution.

Suppose that, for a given hydrophone station, if the underwater explosion equivalent exceeds a certain threshold, it is shown that the signal could be detected. Take the right side of equation (5) as a continuous function of time, and the equation could be written as follows:

$$W(t) = \left[\frac{10^{(SL(t)/20)-12}}{K} \right]^{3/\alpha}. \quad (6)$$

$W(t)$ is defined as the ‘threshold parameter,’ which represents the upper equivalent limit for a hypothetical underwater explosion at a given location (target region) as a function of time. If an actual explosion event does occur at this site, $W(t)$ for the time that the signal arrivals is the event equivalent for the station. If the explosion event is not detected, there will be

$$\hat{W} \leq W(t). \quad (7)$$

Using a statistical approach and assuming statistical independence observation, the upper equivalent limit is obtained by considering the following function:

$$g(W, t) = P\left(\frac{\hat{W} > w(t)}{W}\right) = \phi\left(\frac{W - W(t)}{\sigma}\right), \quad (8)$$

where W is the event equivalent, σ is the standard deviation of the assumed equivalent distribution for the station, and ϕ denotes the standard (0, 1) normal distribution functions. The function $g(W, t)$ is the probability that a given (hypothetical) explosion event of equivalent W at time t would generate a signal level that exceeds the noise level. This means the hydrophone station can detect the explosion at time t . For a given t , the function $g(W, t)$ is a monotonically increasing function of W , with values between 0 and 1. A 90 percent upper limit at time t is defined as the solution to equation (8) for which $g(W, t) = 0.90$; the solution of this equation is a function of time t and is called the equivalent threshold curve of the target region monitored by the station. Through the threshold curve, the ability of the station to monitor the underwater explosion event can be known, and the equivalent of the event can also be estimated.

3. Data and Application

Both HA08 and HA01 hydrophone stations of the IMS recorded the signal produced by the underwater explosion in the coastal area of the city of Carnarvon, Western Australia, on November 10, 2008. The distance between HA01 and this explosion position is about 1150 km, 4700 km for HA08. With the explosive type as TNT, some studies have estimated the equivalent of this underwater explosion based on the bubble oscillation period. Figure 3 shows the time delay of the explosion estimated by the cepstrum technique, including three peaks marked as $T1$, $T2$, and $T3$, respectively. The first peak appears in 0.46 s, the second peak appears in 0.89 s, and the third peak appears in 1.33 s, which means that the first bubble oscillation period is 0.46 s, and the second bubble oscillation period is 0.43 s calculated by (0.89 s – 0.46 s). From these two periods, the explosion equivalent was estimated about 379 kg TNT. Some other studies estimated the equivalent to be 360 kg TNT [13]. In this paper, the new method is used to estimate the equivalent with the capability of monitoring capacity of these two hydrophone stations, in which the sound source level is obtained by equation (1); that is, $SL = TL + (NL - DI) + DT$. In this case, IMS hydrophone stations have the same

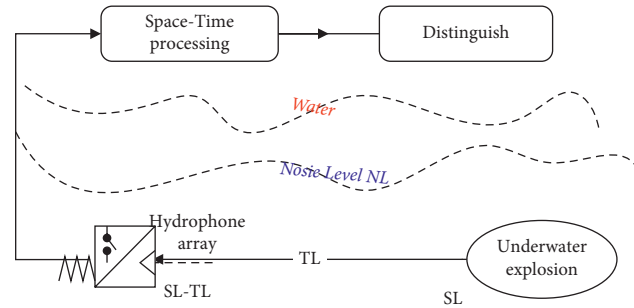


FIGURE 2: Function of the passive sonar.

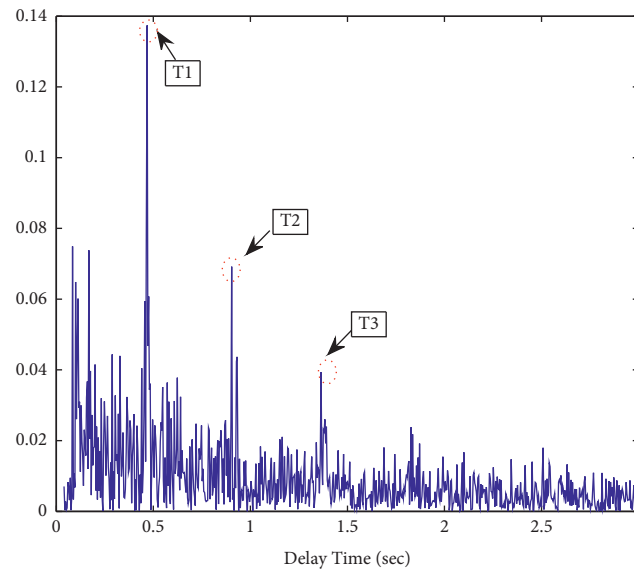


FIGURE 3: Delay time of the underwater explosion on November 10, 2008, recorded by the H08S station.

reception level for all directions so that the item DI could be neglected in this equation. DT is set to 8 dB, indicating that a signal with $SNR = 8$ dB could be detected by the station obviously. In order to simplify the calculation, the 1D transmission loss model was used in this paper which was generated from a cylindrical spreading relationship outlined by Urick [14]. That is, $TL = 10\log(\Delta) + 100.46$, and Δ is the distance in degrees. From long-term data records of the hydrophone station, the background noise level is under 90 dB most of the time (Jeffrey A. Hanson, Colin L. Reasoner, and J. Roger Bowman, "Hydro-acoustic propagation loss from reflection and transmission over shallow bathymetry in the Indian Ocean," 28th Seismic Research Review: Ground-Based Nuclear Explosion Monitoring Technologies; Patrick, "Implementation of a hydro-acoustic monitoring system for the Comprehensive Nuclear Test Ban Treaty," Comprehensive Nuclear Test Ban Treaty Organization, Vienna International Center, A-1400 Vienna, Austria); therefore, we could set $NL = 80$ dB, equal to the average noise level, but in this paper, we use the real-time data received by the hydroacoustic station as the background noise level and deduct the instrument response. The underwater sound speed is set to 1500 m/s. The evaluation results are shown in figures.

- (1) As shown in Figure 4, according to the time of maximum signal amplitude, there is a peak on the threshold trace of HA08S, whose value is about 360 kg TNT, equivalent to the estimation results of current methods. For other times, the value of the threshold trace is less than 1 kg TNT, which means that, during this time, the monitoring capability of the HA08S station is about 1 kg TNT based on the noise level.
- (2) Furthermore, as shown in Figure 5, according to the time of maximum signal amplitude, there is also a peak on the threshold trace of HA01W, whose value is about 377 kg TNT, close to the estimation results of current methods. For other times, the value of the threshold trace is less than 10 kg TNT, which means that, during this time, the monitoring capability of the HA01W station is about 10 kg TNT.

The results show that the evaluation of the HA08 station is better than that of HA01 when the distance between the underwater explosion and HA08 is larger than to HA01. The reason is that the background noise level of HA01 during this time is greater than HA08 as shown in Figure 6. Therefore, the monitoring ability to this site of HA01 is lower than HA08.

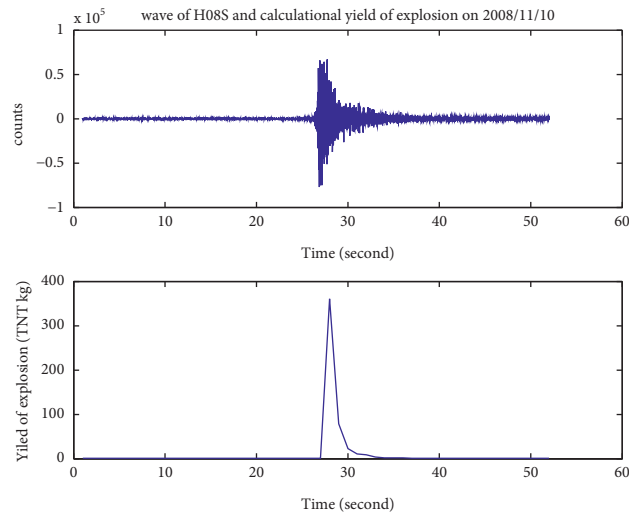


FIGURE 4: Equivalent estimation monitoring threshold trace in 90% probability of H08S station.

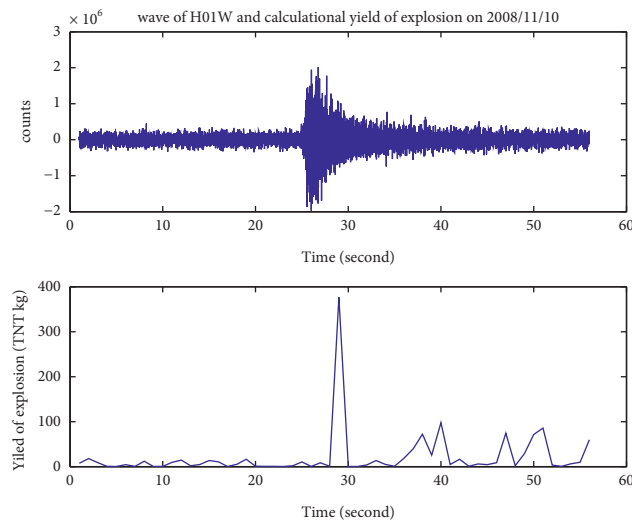


FIGURE 5: Equivalent estimation monitoring threshold trace in 90% probability of the H01W station.

Another example could directly prove the superiority of this new method. On November 15, 2017, the disappearance of the Argentine submarine ARA San Juan shocked both at home and abroad. Nielsen et al. [15, 16] carried out relevant research on the suspicious signal of this event detected by IMS hydroacoustic stations HA10 and HA04. Argentine navy conducted a controlled underwater explosion test with the source position at 45.6°S, 59.4°W, depth about 35 m, and equivalent about 108 kg to 146 kg on December 1, 2017, and this calibration signal was also recorded by HA10 and HA04 [17, 18]. Although the HA10 station is far away from the test, more than 6000 km, it still clearly recorded the explosion signal; the raw data and spectrum of HA10N (north hydrophone of HA10) are displayed in Figure 7. According to this graph, there are two groups of signals, whose spectrum range is relatively wide, from 1 Hz to 100 Hz, which is fully consistent with the underwater explosion signal

characteristics of IMS hydroacoustic station monitoring. The first group of signals comes from the explosion itself, and the second one has low amplitude, which is due to the delay of signal reflection to the station. At the same time, because of the long distance, HA10 cannot record the clear oscillation bubble of this underwater explosion. Figure 8 shows the cepstrum analysis of HA10N1, one of the sensors in the HA10N station, there is only one peak in this figure, and the time is 0.45 s, which is consistent with the first bubble oscillating period generated by the controlled explosion. It means that the method of estimating the explosion equivalent by using the bubble oscillation period is invalid. Then, the TM method is used to estimate the equivalent of this test event; the result is shown in Figure 9. According to the time of maximum signal amplitude, there is also a peak on the threshold trace of HA10N, whose value is about 143 kg TNT. This data processing result was consistent with [14].

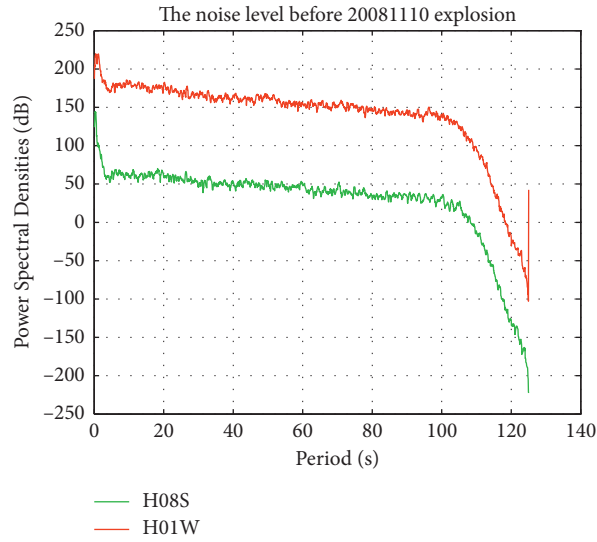


FIGURE 6: Background noise level compared between the H08 south station and H01 west station before the blast on November 10, 2008.

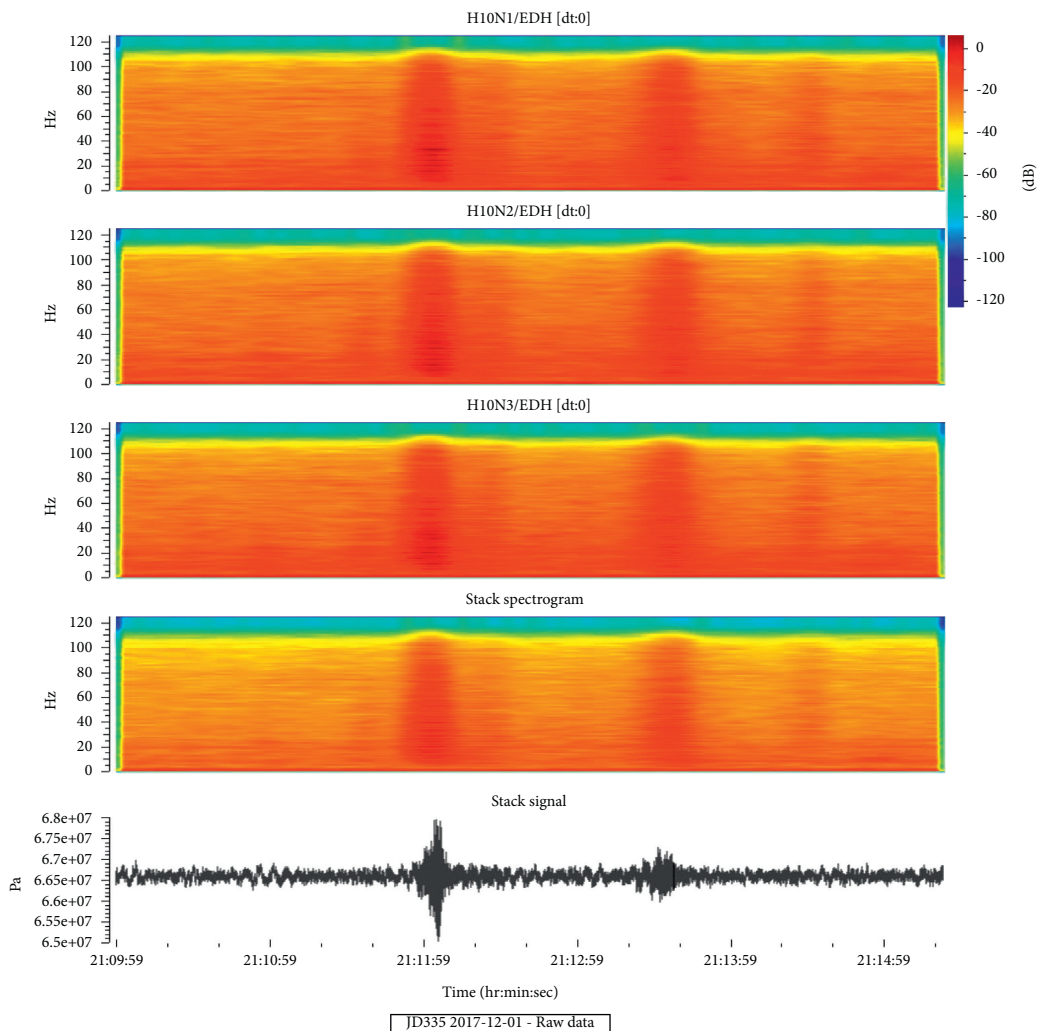


FIGURE 7: The raw data and spectrum of December 1, 2017, recorded by the H10N station.

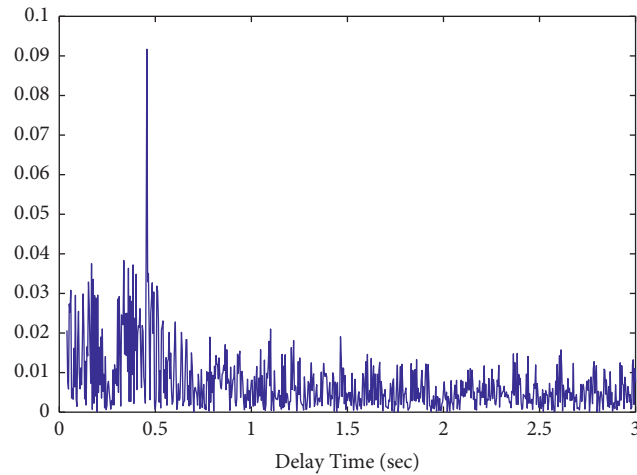


FIGURE 8: Delay time of the underwater explosion on December 1, 2017, recorded by H10N1.

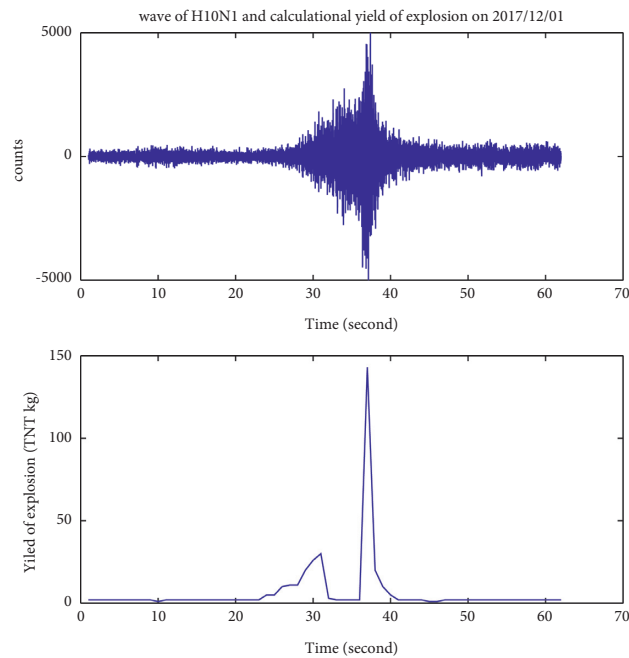


FIGURE 9: Equivalent estimation monitoring threshold trace in 90% probability of the H10N1 station.

4. Conclusions

In this paper, the TM technique was used to estimate the equivalent of the underwater explosion by analyzing the received real-time data. It is not necessary to accurately obtain the first and second bubble pulsation periods, which proves to be of low processing complexity with high equivalent estimation accuracy. Furthermore, this method could be extended to analyze the monitoring ability of the hydroacoustic station. Through the calculated equivalent estimation monitoring threshold curve, the monitoring ability of the hydroacoustic station to the target region can be obtained in near real-time.

Data Availability

The data used to support the findings of this study are available from the corresponding authors upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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