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An evaluation of the Signals Used for Tsunami Warnings in New Zealand

Jeffrey Mahn

For:

David Coetzee
Manager, Capability & Operations
Ministry of Civil Defence & Emergency Management
Level 9, 22 The Terrace
Wellington 6145

Summary

A danger signal is used to indicate the possibility or the occurrence of a dangerous situation which requires appropriate measures for the elimination or control of the danger. Therefore, auditory danger signals must be designed to be clearly heard and to elicit the most appropriate action from the target listeners. A list of requirements and recommendations for a tsunami danger signal were compiled from relevant, international standards and from the findings of research studies from around the world. The requirements are summarized below:

- The signal shall be distinct from all other sounds and any other signals.
- The meaning of the danger signal shall be clear.
- The danger signal should include two frequency components in the 500 Hz to 2500 Hz range.
- The danger signal shall have sufficient energy below 1500 Hz to be heard by people with hearing loss.
- Pulsating danger signals should be preferred to signals that are constant in time. The repetition shall be between 0.25 s and 2 s.
- Varying fundamental frequencies should be selected for the danger signal.
- The danger signal should include frequency components below 500 Hz for better coverage.
- The danger signal should have a frequency component between 224 Hz and 355 Hz for transmission through windows.
- The danger signal should convey urgency.

Several of the tsunami danger signals currently in use in New Zealand were evaluated. None of the existing signals evaluated met all of the requirements for a danger signal, but the signal used in Northland met most of the requirements. Adding a second tone between 224 Hz and 355 Hz to the Northland signal will make it fully compliant with the requirements for a danger signal. Alternatively, the design of a danger signal that will meet all of the requirements has been proposed. It is recommended that verbal warnings which fully comply with the standard, ISO 9921 be integrated with the non-verbal tsunami danger signals.

An advantage that the electronic sirens have over mechanical sirens is that the tsunami danger signal they produce can be modified to comply with the requirements for a danger signal. Furthermore, the electronic sirens can integrate verbal messages which have been shown to increase the effectiveness of danger signals. Due to the limitations of mechanical sirens and since tsunami danger signals generated by mechanical sirens do not meet the requirements for a danger signal, it is recommended that no additional mechanical sirens be installed for the generation of tsunami danger signals and only electronic sirens be considered in the future.

Regardless of the tsunami danger signal which is chosen, the inclusion of an education program for the people who live and work in the siren coverage area is critical. Educating people about the sound of the signal, its meaning and the appropriate response to be taken must be an integral part of any plan to install tsunami warning sirens in a community.

Table of Contents

1. Introduction

Auditory danger signals are useful for warning people of the possibility or the occurrence of a dangerous situation because hearing is a primary warning sense. It does not matter whether people are concentrating on an important visual task, or relaxing with their eyes closed. Either way, if a danger sound occurs it will be detected automatically and routed through on a priority line to the brain [1]. Auditory danger signals are designed to elicit the most appropriate action from the target listener. Generally, the better the design of the danger signal, the more likely the sound is to be detected, the more information concerning the situation can be extracted by the listener and the better the response of the listener [2].

There are three types of information that auditory danger signals can carry simultaneously: meaning, urgency and location [2]. Meaning refers to the ability of a person to understand the semantic information contained in the danger signal, which is learned through association. Urgency refers to how alerting, insistent or attention-grabbing a danger signal is and allows the recipient to immediately decide how safety-critical a particular event is or how quickly a response to the danger signal is required. Sound source location information may be designed into the danger signal and this information can be used by the listener to improve their response.

In principle, acoustic signals have to meet three criteria to be effective. Recipients have to detect the signal, interpret the signal and take appropriate action [3]. The reliable recognition of a danger signal requires that the signal is clearly audible, is sufficiently different from other sounds in the environment and has an unambiguous meaning. However, the efficiency of danger signals can be affected by several factors, such as the presence of hearing loss amongst people and the masking effects of the background noise in the working environment [4]. Furthermore, the danger signal is attenuated with distance from the source due to the characteristics of the signal, surrounding surfaces and meteorological factors [5].

Tsunami danger signals in New Zealand are produced by single sirens or arrays of sirens. There are currently over three hundred tsunami warning sirens installed in the coastal areas of New Zealand with over fifty additional sirens planned for future installations. The sirens are predominantly located in the major population areas as shown in Figure 1. The figure also shows the different tsunami danger signals currently in use in the different parts of the country.

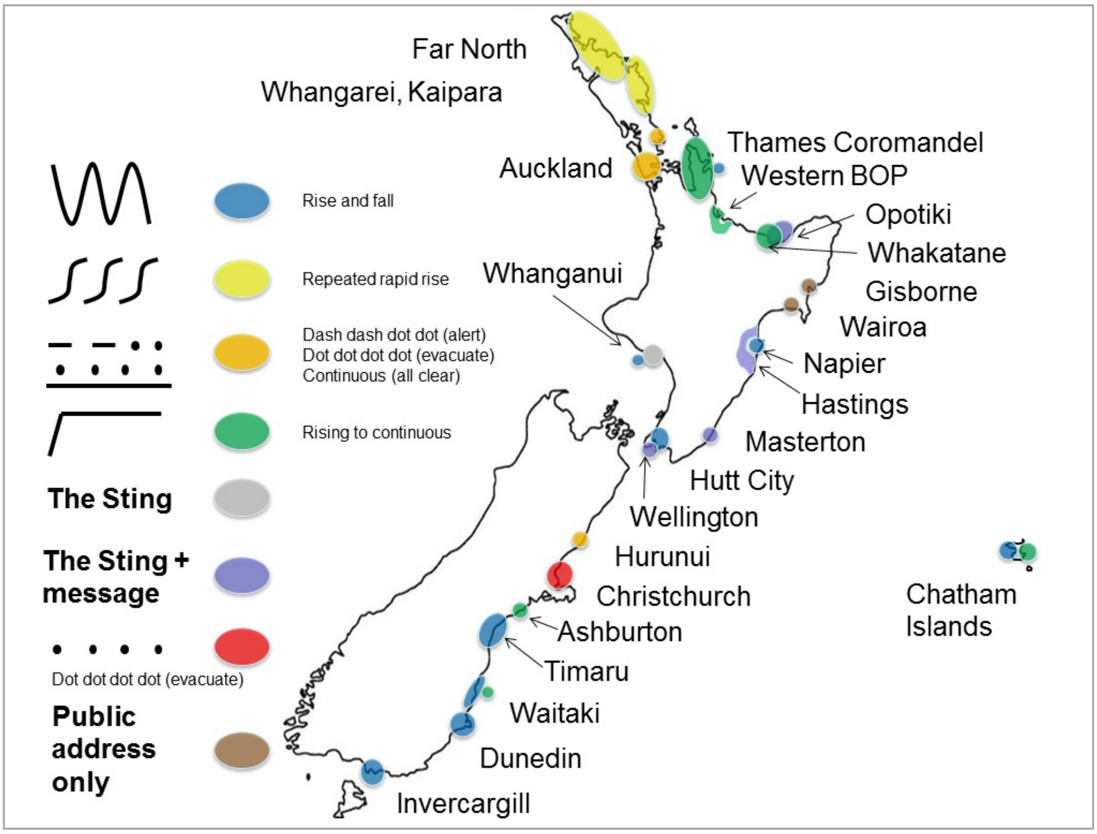

Figure 1: Location of current tsunami warning sirens in New Zealand. The colours indicate the different signals which are used throughout the country. From Morris [6]. Used with permission.

The sirens which are installed or which are planned for future installations include two hundred and ninety-two electronic sirens and one hundred and twenty-three mechanical sirens [6]. There are an additional eleven electronic sirens and five mechanical sirens in the early proposal stage. The electronic sirens are generally programmable and are capable of producing dangers signals of varying patterns and with multiple tones. Furthermore, electronic signals can integrate verbal messages with the non-verbal signal. On the other hand, mechanical sirens such as those installed in Thames Coromandel generate signals which can not be altered. Mechanical sirens manufactured by different companies will produce signals with different frequency tones.

In 2013, the Ministry of Civil Defence & Emergency Management agreed to develop a standard for the use of sirens in tsunami warnings following requests from the Waikato Civil Defence Emergency Management group and the Tauranga City Council. The standard will provide guidance on how sirens should be utilized within tsunami warnings if groups or Territorial Authorities (TAs) are using or intending to use them [6]. One proposed component of the standard is the recommendation of a standardized signal for the tsunami warnings.

The Acoustics Research Group was commissioned to compile the requirements for a danger signal and to review the tsunami danger signals currently used in New Zealand. This report begins with a review of the relevant international standards as well as a review of past research studies relevant to the design and the effectiveness of danger signals. Based on the international standards, a list of requirements for a tsunami danger signal was developed as listed in Section 2. In addition, a list of recommendations based on the findings of the research studies is listed Section 3. There are a number of different tsunami danger signals currently in use in New Zealand and many of these signals were analyzed for comparison with the list of requirements and recommendations in Section 4. Section 5 summarizes the requirements for verbal communication to be included in danger signals. Lastly, Section 9 reviews the need for education to be an integral part of the tsunami warning system.

2. Danger Signal Requirements

There are a number of standards which have been published by the International Standards Organization which specify the requirements for effective danger signals. The standards include [7-9]:

- ISO 7731:2003 Ergonomics -- Danger signals for public and work areas -- Auditory danger signals. This International Standard specifies criteria applicable to the recognition of auditory danger signals, especially in cases where there is a high level of ambient noise.
- ISO 9921:2003 Ergonomics -- Assessment of speech communication
- ISO 11429:1996 Ergonomics -- System of auditory and visual danger and information signals

In addition, the Technical Bulletin, Outdoor Warning Systems published by the Federal Emergency Management Agency of the United States [10] provides guidance for the design, placement and maintenance of outdoor sirens. There have also been a number of studies about the design of warning and danger signals which have been published in journals. These papers have also been referenced for this study.

2.1. General

ISO 7731 states that the nature of the danger signal shall be such that people in the reception area can hear and react to the signal as intended. Furthermore, ISO 11429 states that auditory signals shall be rapidly recognizable under all environmental conditions anticipated for their use. The recognition of a signal depends on many physical and psychophysical characteristics. If people with hearing impairments are likely to be present in the coverage area, special considerations should be taken. The characteristics of the audible signal shall be adapted to take account of the characteristics relevant to the situation.

Meeting the alerting needs of special need populations such as those with hearing loss is essential [11]. Hearing loss involves both elevation of hearing thresholds and loss of frequency selectivity. For example, noise induced hearing loss begins with a reduction in the hearing ability around 4000 Hz and with continued exposure, this reduction increases and widens across the frequency range [5]. Older adults generally have trouble discerning sounds and voices in the extreme frequency ranges, though the upper ranges tend to be affected first. This includes sounds above 4000 Hz, frequencies common to human speech. To be heard by people with hearing loss, danger signals with frequency components around 4000 Hz should be avoided or should also include sufficient signal energy below 1500 Hz. Danger signals that include attention capturing alerts or voice information should be carefully tested to make sure they meet the needs of older users [12].

2.2. Audibility

ISO 7731 states that the danger signal shall be clearly audible. Therefore the A-weighted sound pressure level of the signal must exceed the ambient noise level so that the signal can be heard. Danger signals are considered to be clearly audible in the signal reception area if their A-weighted sound pressure levels exceed the effective masked threshold by 15 dB or more and if the A-weighted sound-pressure level of the signal is not lower than 65 dB. Note that the effective masked threshold is the level of an auditory danger signal just audible over the ambient noise. To this end, ISO 7731 [7] requires the following:

1. The A-weighted sound pressure level of the danger signal shall not be lower than 65 dBA at any position in the signal reception area.
2. In addition, at least one of the following conditions shall be met to ensure that the sound pressure level of the danger signal is higher than the sound pressure level of the ambient noise:
    a. For measurements of the A-weighted sound-pressure level [method a) in ISO 7731 Section 5.2.2.1], the difference between the two A-weighted sound-pressure levels of the signal and the ambient noise shall be greater than 15 dB $(L_{S,A} - L_{N,A} > 15\ dB)$ where $L_{S,A}$ is the A-weighted sound level of the auditory danger signal, $L_{N,A}$ is the A-weighted ambient noise, both in decibels (dB re 20 µPa).
    b. For measurements of the octave-band sound-pressure level [method b) in ISO 7731 Section 5.2.3.1], the sound pressure level of the signal in one or more octave-bands shall exceed the effective masked threshold by at least 10 dB in the octave-band under consideration $(L_{Si.oct} - L_{Ti,oct} > 10\ dB)$ where $L_{Si.oct}$ is the level in octave-band i of the auditory danger signal, $L_{Ti,oct}$ is the level in octave-band i of the masked threshold, both in decibels (dB re 20 µPa).

c. For measurements of the 1/3 octave-band sound-pressure level [method c) in ISO 7731 Section 5.2.3.2], the sound pressure level of the signal in one or more 1/3 octave-bands shall exceed the effective masked threshold by 13 dB in the 1/3 octave-band under consideration $\left(L_{Si.1/3oct} - L_{Ti,1/3oct} > 10\ dB\right)$ where $L_{Si.1/3oct}$ is the level in 1/3 octave-band i of the auditory danger signal, $L_{Ti,1/3oct}$ is the level in 1/3 octave-band i of the masked threshold, all in decibels (dB re 20 μPa).

3. The maximum signal level shall not exceed 118 dBA in the signal reception area.

The requirement of ISO 7731 that the signal level be at least 15 dBA above the effective masked threshold is consistent with the findings of other studies (see for example, Patterson and Mayfield [1]). However, Tierney [13] reported that yet other studies have recommended that the signal level should be a minimum of 15 to 25 dB above the background noise level. Haas and Edworthy [14] found that the higher pulse levels resulted in significantly greater perceived urgency, which may be applied to the practical application of the signal design within the recommended sound pressure level limits. Zheng, *et al*. [4] recommend that a signal level 25 dB above background noise level should be considered as an upper limit per frequency component of a signal. However, a common problem described in the literature is the deliberate setting of signal levels excessively high, resulting in extremely aversive signals and disrupted speech communication when the alarms fired [4]. This can be avoided by setting the signal level correctly based on measurements of the background noise levels in the coverage area.

Danger signals with signal levels that increase more than 30 dB in 0.5 seconds or signals that use too high a sound pressure level can elicit a startle reaction [7]. In the natural environment a rapid rise to a high sound level is characteristic of a catastrophic event in the listener's immediate surroundings. The natural response to such an event is an involuntary startle reflex in which the muscles are tensed in preparation for a blow or a quick response. Instantaneous responses often prove incorrect, and so they are specifically discouraged, especially since they slow response times. Patterson and Mayfield [1] recommend that risk of creating a startle response can be reduced by starting the generation of the warning signal at a comparatively low level and increasing the level of subsequent pulses. The basic pulse should also be given a rounded top rather than an abrupt onset or offset to reduce the risk of a startle reaction. ISO 11429 states that the initial intensity of the sound should not be too high but should increase during the duration of the signal.

There are other factors which influence whether a danger signal is heard including the frequency and/or the temporal distribution of the danger signal [7] and the hearing loss in the recipient population [15]. In an assessment of audible alarms, Burgess and McCarty [5] found that people with significant hearing loss could had difficultly detecting signals with a noise level lower than 85 dBA. However, it was found that as long as the signal level was above 85 dBA and at least 15 dBA higher than the background noise level, then individuals with significant hearing loss would not have difficulty in detecting the signal.

To ensure compliance, Territorial Authorities must determine the ambient noise levels within the intended coverage area of the sirens in accordance with Section 5 of ISO 7731. For measuring the ambient noise level, the maximum reading with time weighting "Slow" shall be used. Calculations shall be based on the samples taken from a representative number of measurements. The background sound pressure levels will typically be higher in the daytime than during the night.

From a practical standpoint, the requirements stated in ISO 7731 for the signal level will affect the distribution of sirens within the signal reception area. The effective range of a warning device is dependent on three major components: the rated warning device noise level, the atmospheric conditions, and the local terrain [10]. However, as well as being fundamentally defined by the output level of the sound at source, effective distance can also be influenced by the frequency content of the signal, the propagation of the sound source through the air and the sound reduction index of obstacles (such as walls or windows) present between the source and the listener [2]. The attenuation with distance can be predicted by outdoor noise models such as ISO 9613-2:1996 [16].

To ensure compliance, ISO 7731 Section 6.5 states that manufacturers and agents of sound sources for danger singles shall present at least the following information in their datasheets:

- the minimum and maximum values of the A-weighted sound-power level $(L_{W,A})$ or, if not available, the A-weighted sound-pressure level $(L_{S,A})$ measured in the free field at a distance of 1 m from the sound source in the main direction of radiation
- spectral components, by octave or 1/3 octave, in the centre frequencies from 125 Hz to 8000 Hz measured at a distance of 1 m from the sound source in the main direction of radiation
- the temporal envelope of the danger signal for a representative time period.

Section 5 of ISO 7731 specifies how the data should be measured by the manufacturers.

2.3. Distinctiveness

ISO 7731 states that the danger signal characteristics such as signal level, frequency spectrum and temporal pattern shall be designed to stand out from all other sounds in the reception area and shall be distinctly different from any other signals.

People are being constantly bombarded by different sounds during the day and in order for people to correctly react to a danger signal, they must first recognize its importance as compared to all of the other sounds they hear. Humans are capable of selectively attending to certain acoustic sounds while ignoring others [17]. For listeners to selectively attend to a danger signal in the midst of competing sounds, the danger signal must be distinct and should be designed to capture the attention of the listeners.

For this reason, a study by Lazarus and Höge [3] recommended against the use of impulse sounds since people often associate impulse sounds with pleasant sounds such as the end of work, celebration or joy. For example, a person working in a factory where the end of the work day is announced by a horn blowing would associate a horn blowing as being a good thing (the end of the work day).

2.4. Unambiguity

ISO 7731 states that the meaning of the danger signal should be clear.

Studies such as that by Gregg, *et al*. [18] found that there needs to be a single warning signal for local tsunamis that alerts the at-risk people to evacuate to an area where they can learn more about the emergency situation at hand. As ambiguity regarding interpretation of the warning increases, the greater is the likely delay in public response. Such ambiguity may contribute to increased use of telecommunications systems to seek further information (i.e., confirm and personalize the warning), which is a concern because it may clog the system and prevent the exchange of official information. Gregg, *et al*. note that the one danger signal used in Hawaii makes educational outreach easier than if there were multiple signals in use because the public is not required to learn and to remember the different signals and responses.

Examples of problems of ambiguous danger signals can be found in stories from past tsunami disasters, such as that in Hilo, Hawaii in May 22, 1960 [19]. At 6:47 p.m. Hawaiian time, the U.S. Coast and Geodetic Survey issued an official warning that waves were expected to reach Hilo at about midnight. Around 8:30 p.m., coastal sirens in Hilo sounded and continued to sound intermittently for 20 minutes. When the first wave which was only a few feet high arrived just after midnight, hundreds of people were still at home on low ground in Hilo. Others, thinking that the danger had passed, returned to Hilo before the highest wave of the tsunami struck at 1:04 a.m. on May 23. People reported that police officers told people that the danger had passed. In all, 61 people in Hilo died and another 282 were badly hurt. These losses occurred, in part, because the warning sirens in Hilo on the evening of May 22, 1960, were interpreted differently by different people. Although nearly everyone heard the sirens, only about one third of those that heard the signal thought it was a signal to evacuate without further notice. Most thought it was only a preliminary warning to be followed later by an evacuation signal.

Multiple studies point to the need for public education about danger signals to reduce confusion about the meaning of and proper response to a danger signal. This will be discussed further in Section 9.

2.5. Moving Sources

ISO 7731 states that the characteristics of a danger signal from a moving signal source such as a rotating siren or a siren mounted on a vehicle shall be recognizable, regardless of the speed or movement direction of the source.

2.6. Spectral Characteristics

ISO 7731 requires that danger signals should include frequency components in the 500 Hz to 2500 Hz frequency range. However, generally two dominant components from 500 Hz to 1500 Hz are recommended.

Some studies (for example [1, 7, 20]) recommend as many as four frequency components. A warning sound that has four or more components in the appropriate level range, and which are spread across the spectrum, is much less likely to be masked by a spurious noise source than one in which all of the energy is concentrated at one frequency [1].

In addition, there are several notes in ISO 7731:

- The greater the difference in level between the signal tones and the ambient noise in the same octave band, the easier it is for people to recognize the danger signal. Therefore, it is advantageous to design the danger signal so that the frequency components differ from the dominant frequency components of the ambient noise.
- In the case of persons having hearing loss, sufficient signal energy should be present in the frequency range below 1500 Hz.
- Due to the internal masking of the hearing organ, low-frequency components of the ambient noise may mask higher frequency components of the danger signal. Hearing loss can also show an effect that may be additional to the masking effect.

2.7. Temporal Characteristics

ISO 7731 has several requirements for the temporal characteristics of danger signals:

1. In general, pulsating danger signals should be preferred to signals that are constant in time. The repetition frequencies shall be in the range from 0.5 Hz to 4 Hz. The pulse duration and the pulse repetition frequency of the danger signal shall not be identical with the pulse duration and the pulse repetition frequency of any periodically varying ambient noise in the signal reception area.
2. When higher pulse repetition frequencies coincide with a long reverberation time in the signal reception area, the pulsation will be smoothed out. Hence, discrimination between signals with similar frequencies, but different pulse repetition frequencies, will decrease.
3. In general, danger signals with varying fundamental frequencies should be selected. For example, danger signals with a fundamental frequency sweep in the range of 500 Hz to 1000 Hz, with four harmonics, will give adequate signal audibility.
4. Temporary masking of the danger signal by ambient noise may be permitted in certain cases, for example, if there are short time variations of the ambient noise. However, in such cases, care shall be taken to ensure that, not later than 1 s after the signal has started, the danger signal complies with the other requirements stipulated in Sections 2.1 to 2.5 for a period of at least 2 s. The temporal characteristics of the danger signal should depend on the duration and type of the danger.

In regard to point 1, Edworthy and Meredith [21] evaluated continuous tone signals which have a constant pitch which continues for the duration of the signal. They concluded that not only is the continuous tone signal bad as an attention getting device - our perceptual system is geared towards change, rather than constancy - it is bad from a cognitive point of view. Memory for pitch decays over time and therefore, people may not immediately recognize the signal as the same continuous tone danger signal that they heard last year when the system was being tested.

In regard to points 1 and 2, reverberation and amplitude fluctuations also have pronounced effects on the temporal properties of sound, sometimes called degradation rather than attenuation. Reverberation results from multiple refractions and reflections of sound from objects in the path of transmission. The objects can include buildings or other manmade structures or natural objects such as trees. Therefore, sirens located in built-up or forested areas will be more affected by reverberation than sirens located in open areas. As a result of the reverberation, sound no longer arrives at the receiver along a single, direct path. Instead, it arrives from a wide angle along many paths of different lengths. Some of the sound is thus delayed, in relation to the rest, in reaching the receiver. The result is a smearing of any temporal patterns in the sound. Wiley [22] explains that the smearing of temporal patterns is why birds in forests, especially broad-leaved forests, are less likely to incorporate rapid repetitions of notes at any one frequency in their songs than are birds of grasslands. ISO 11429 notes that changes to the perceived character of a signal are possible, especially when separate sound sources are used as would be the case with multiple sirens being used.

2.8. Review of the Signal

ISO 7731 states that the effectiveness of the danger signal shall be reviewed at both regular intervals and whenever a new signal (whether a danger signal or not) or a change in the ambient noise occurs, or any other relevant changes are made.

2.9. Duration

ISO 7731 specifies that the temporal characteristics of the danger signal should depend on the duration and the type of the danger. ISO 8201 [23] which specifies the requirements for an audible emergency evacuation signal for buildings or public areas specifies that the duration of the audible emergency evacuation signal shall correspond to the period of time appropriate for the evacuation of the building or outdoor area, but shall not be less than 180 seconds. The FEMA Outdoor Warning Systems Technical Bulletin [10] states that in the case of an attention or alert warning (not an evacuation signal), the duration of the signal is to be 3 to 5 minutes.

3. Danger Signal Design

ISO 7731 specifies the framework for the design of a danger signal in terms of the intensity, spectral characteristics and temporal characteristics. Working within these requirements, there are four signal properties that can be used to ensure that the danger signal will be successfully heard and understood by the people in the coverage area. These signal properties include the audibility, sound pattern design, sound source placement and usage [2].

3.1. Audibility

There are two considerations when designing for the audibility of the danger signal. The first is compliance with the requirements of ISO 7731 for the signal level in the coverage area. The second is the audibility of the danger signal inside of dwellings within the coverage area.

3.1.1. Signal level in the coverage area

ISO 7731 stipulates both a minimum and a maximum signal level. Furthermore, the maximum signal level a siren can generate is limited by the siren design. Therefore, it is not possible to simply increase the signal level at the source beyond the limits of ISO 7731 and the siren itself to ensure both that the signal level is at least 65 dBA and at least 15 dBA above the threshold level throughout the coverage area. However, to achieve the minimum levels set forth by ISO 7731, it is possible to specify the frequency components of the danger signal to reduce the attenuation of the signal with distance from the source.

For any level of background sound, attenuation sets a distance beyond which the signal can no longer be detected above the effective masked threshold [22]. The attenuation of the warning signal over distance depends on many factors including characteristics of the source, surrounding surfaces and meteorological factors [5]. Furthermore, sound propagation is also affected by scattering by buildings, trees, etc. [24]. The total attenuation of the signal depends on the frequency content of the signal.

The attenuation with distance can be predicted by outdoor noise models such as ISO 9613-2:1996 [16] as shown in Figure 2. The assumptions that were made for the calculation of the attenuation shown in the figure included that the source was at a height of 3m, the receiver was at a height of 2m, the ground was porous, the temperature was 15 degrees C and the relative humidity was 20%. This combination of temperature and humidity was chosen to provide the greatest amount of atmospheric attenuation as listed in the standard. It was further assumed that there were no barriers or thick groups of trees between the source and the receiver positions.

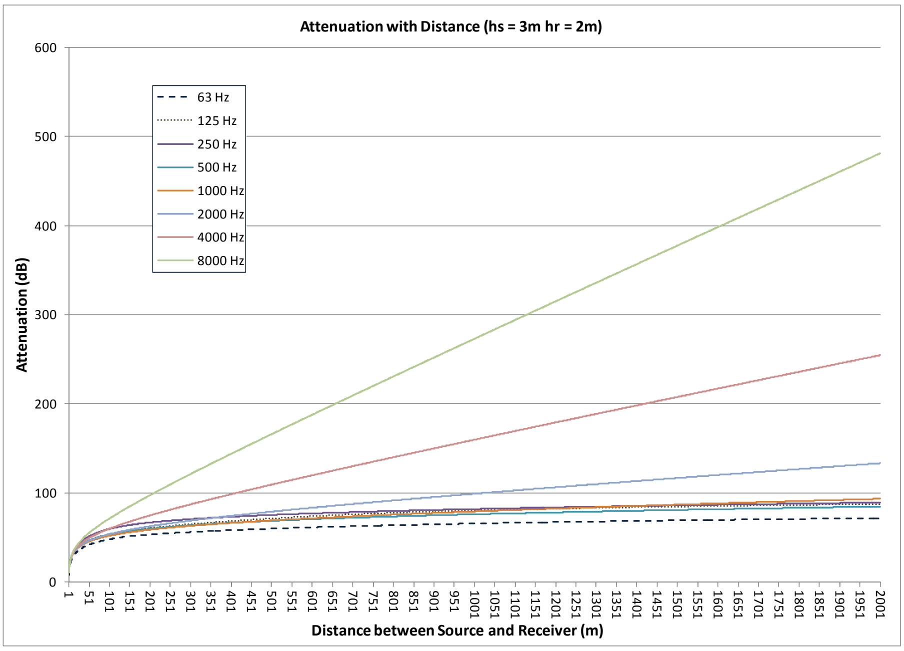

Figure 2: Attenuation (dB) with increasing distance (m) between the source and the receiver.

The data in the figure shows that the higher the frequency, the higher the attenuation with distance. In the octave band above 2000 Hz, sound is severely attenuated at distances greater than 100 m due to atmospheric absorption. The figure shows that the lowest attenuation with distance occurs in the 63 Hz, 125 Hz, 500 Hz, 1000 Hz octave bands. Therefore, the frequency components of the danger signal are extremely important in determining how far that sound will carry through the air and how well it will be heard. Hence, even though average human hearing extends well beyond their range, most sirens produce signals within the frequency range from roughly 300 to 1,000 Hz [10].

Consideration also needs to be given to the height of the sound source. Fricke [25] showed that the height of the siren affects the rate of attenuation of the danger signal. Increasing the height of the source will have the advantage of decreasing the attenuation with distance as shown in Figure 3.

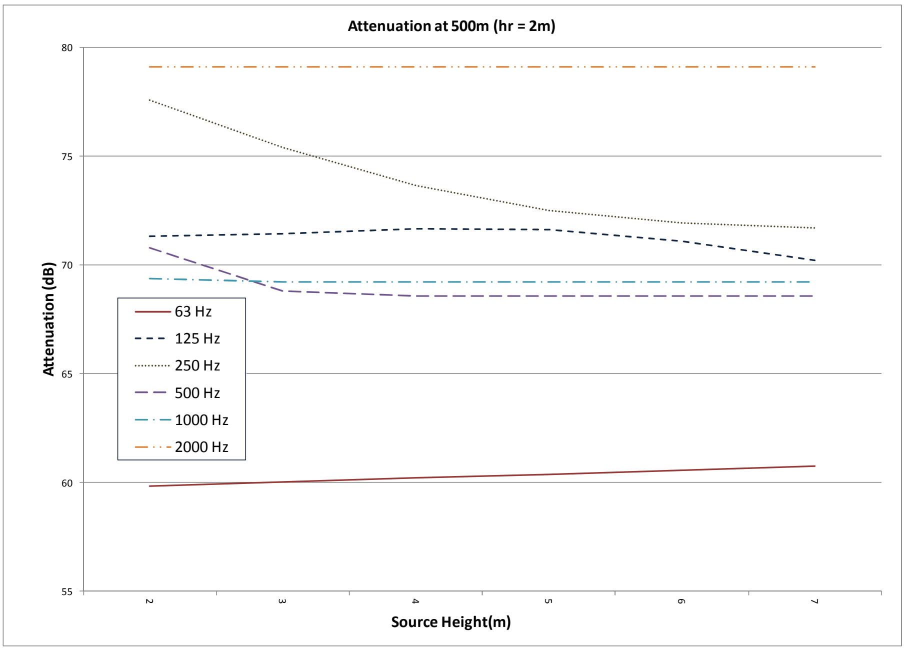

Figure 3: Change in the attenuation at a distance of 500m due to the change in the height of the source.

The figure shows that increasing the height of the source decreases the attenuation, especially in the 250 Hz and the 500 Hz octave bands. In the octave bands above 1000 Hz, the height of the source has no affect on the attenuation. Therefore, it would be advantageous to increase the height of the siren as much as possible.

3.1.2. Signal levels inside dwellings

According to a FEMA technical report [10], a critical time of day for alerting an indoor population with an outdoor siren is at night when people are asleep and therefore are least likely to have immediate access to other alerting methods such as radio or television. The signal level inside a dwelling can be significantly less than the level outside the dwelling because façade elements (walls, windows, roof, etc) of buildings act as barriers to sound. Although windows may be open some of the year, this transmission path into buildings can not be counted on year round. Likewise, people inside of motor vehicles are less likely to distinguish the warnings signal from the ambient noise.

Of the façade elements of a building, the element with the lowest sound reduction index is typically the windows. The predicted sound reduction indices of several windows are compared in Figure 4. The higher the sound reduction index, the more difficult it is for sound to be transmitted through the window.

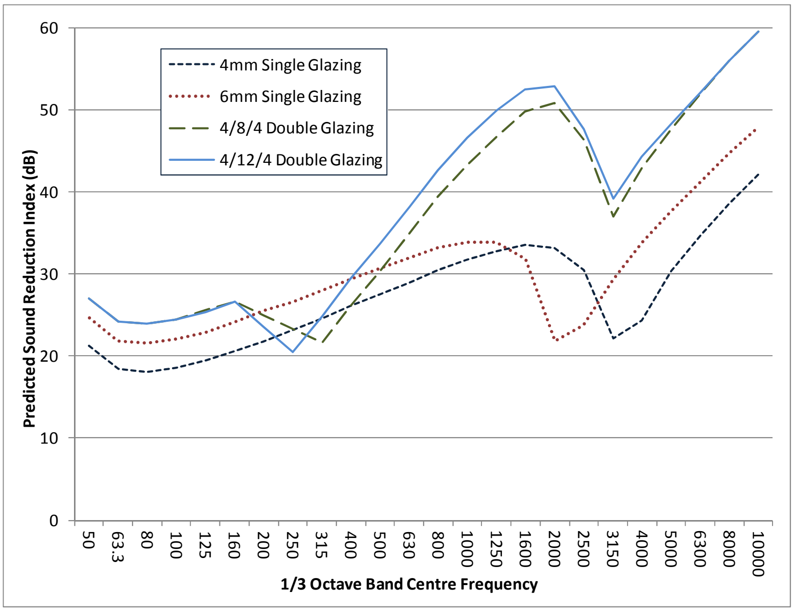

Figure 4: Predicted sound reduction indices of different glazing. The 4/8/4 double glazing has a 4 mm glass, 8 mm air gap, 4 mm glass.

The windows used for the predictions shown in Figure 4 were chosen since they are common in New Zealand. The figure shows that the windows all had dips in the sound reduction index between 2000 Hz and 3150 Hz that could be taken advantage of for the design of the danger signal. However, these dips are located around the same frequencies that are the worst to use for people with hearing loss. Furthermore, the higher frequencies are attenuated better with distance from the noise source. Therefore, a low frequency component in the 250 Hz and 315 Hz 1/3 octave bands where there are dips in the sound reduction indices of the double glazing would be advantageous for increasing the danger signal level inside of buildings. These 1/3 octave bands correspond to a frequency range of 224 Hz to 355 Hz.

To expand the number and types of windows included in the assessment, the laboratory measured sound reduction indices of twenty-two windows commonly used in Canada are compared in Figure 5.

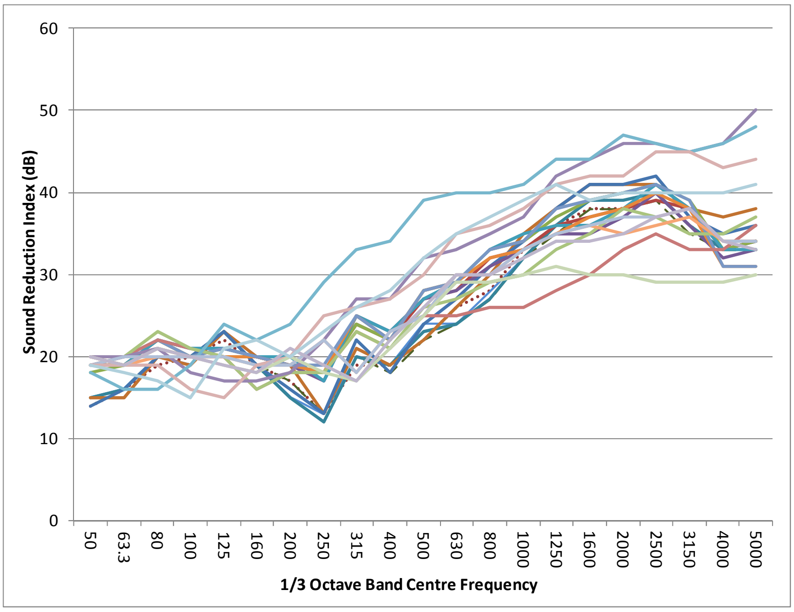

Figure 5: Sound reduction indices of twenty-two windows as measured at the National Research Council of Canada [26].

The sound reduction indices in the figure show that a frequency component in the 250 Hz 1/3 octave band would be advantageous for the transmission of noise through the windows.

Even with a tonal component in the 250 Hz 1/3 octave band, the signal level inside of the dwelling can still be significantly less than that outside the dwelling. For example, if the signal level outside the dwelling is 65 dBA, it is likely that the signal level inside the dwelling will be lower than 40 to 50 dBA. It is for this reason that FEMA [10] notes that sirens can not be counted on to alert people in vehicles or buildings unless the vehicles or buildings are very close to the siren.

3.2. Perceived loudness

Sounds can be perceived by the human ear as being louder than they actual are. The perceived loudness of a sound is influenced by many factors including the absolute frequency, the bandwidth, the duration, the intermittency and the dynamic frequency change of the sound [27]. If different pure tones are played at the same sound pressure level, the different tones will be perceived as having different loudness. Based on equal loudness curves [28], a pure tone at 31.5 Hz would have to have a sound pressure level of 103 dB to be perceived as being equally as loud as a pure tone at 4000 Hz played at 60 dB. Although it would seem advantageous to include pure tones at 4000 Hz since signals at this frequency with low sound pressure levels are perceived as being louder than at any other frequency, there is a problem with perception with people with noise induced hearing loss. Noise induced hearing loss begins with a dip in the hearing ability around 4,000 Hz and with continued exposure, this dip deepens and widens across the frequency range [5]. However, a 4000 Hz tone can be included in a danger signal if there is also sufficient energy in the frequencies below 1500 Hz.

The duration of the signal also affects the perceived loudness of the signal. Longer pulses are perceived as being louder than short pulses. A 1000 Hz tone played for 5 ms at 90 dB is perceived as being equally as loud as a 1000 Hz tone played for 640 ms at 75 dB [29]. Therefore, as stimulus duration increase, the intensity necessary to produce a given level of judged magnitude decreases [30].

Signals with upward sweeping frequency content can produce an increase in loudness, and downward sweeping frequency can produce a decrease in loudness. Therefore, a signal that includes a rising frequency component will be perceived as being louder than a signal that maintains the same pure tone for the duration of the signal. These effects are not predicted by the static equal loudness contours [27].

All of these factors which affect the perception of loudness can be taken advantage of so that the listener can effectively understood and react to the signal danger signal.

3.3. Conveyance of Urgency

One of the stipulations of ISO 7731 is that danger signals can reliably call attention to a dangerous situation. To achieve this goal and to ensure that people will hear and react to the danger signal, the characteristics of the danger signal (pitch, frequency, pulse rate) can be chosen so that the signal is perceived to be urgent in the same way that people intuitively understand that a speaker is angry or distressed by the general level, pitch or speed of the speaker's voice. The greater the perceived urgency of a signal, the shorter the response time to that signal [14].

Prior studies [31-34] have quantified the subjective perception of danger or urgency by introducing different warning sounds playing with the length, period, pauses and frequencies of the signal. It has been found that a wide variety of acoustic pulse and burst parameters have clear and consistent effects on the perceived urgency of auditory warnings, and that participants showed a high level of agreement about the urgency of such warnings [14]. For example, Edworthy *et al.* [35] examined the perceived urgency of thirteen warning signals. The signal which was perceived as having the greatest urgency was a single 2600 Hz pulse of 170 ms duration, repeated 15 times with a 65 ms delay between the end of one pulse and the onset of the next. This signal had both a high frequency tone combined with the most rapid repetition rate of the thirteen alarms evaluated. This finding agrees with the findings of Suied, *et al.* [36] who found that the shorter the delay between the end of one pulse and the onset of the next, the higher the pitch, and the more randomly irregular the frequencies of the harmonics, the greater the perceived urgency. Specifically it was found that a decrease in delay between the onset of one pulse and the onset of the next leads to a decrease in reaction time, probably because of the form of the temporal integration process in the auditory system.

Once the "structure" of an auditory warning has been designed, the perceived urgency could be altered by adjusting the pitch, the intensity, and the speed of the burst. A danger signal designed with these principles in mind could reduce the need for interpretation of urgency and, thereby, reduce the possibility of a misclassification leading to an inappropriate response

[35]. For the design of a tsunami danger signal, it would be advantageous to include a higher frequency component, inharmonics (tones which are not whole number multiples of the fundamental frequency) and short to 0 ms inter-pulse intervals between pulses.

3.4. Frequency Composition

Signals can be described as being either single tone or multiple-tone. Single tone signals consist of one tone presented during the duration of the signal. This definition can be expanded to include repetitions of the same tone, where the tone itself does not change, but simply repeats itself (with silences in between) and, therefore, functions as a single tone. Multiple-tone signals consist of two or more different tones presented during one signal duration. Multiple-tone signals can have a simple or complex harmonic structure, and because of their multiple-tone nature, may carry more information than single tonal warnings [37].

Haas and van Erp [37] note that there are advantages to multiple-tone auditory warnings. Multi-tone signals can be advantageous because they permit variations in signal pitch, loudness, and inter-tone spacing, so that the resultant warning has a distinctive temporal and pitch pattern, which may also make them easy to learn. This multi-tonal distinctiveness confers greater individuality on the warning, increases its potential to signal particular events, and also increases its resistance to masking from environmental noise. ISO 7731 recommends two dominant components from 500 Hz to 1500 Hz. Some studies (for example [1, 7, 20]) have recommend multi-tone signals with as many as four frequency components and their harmonics. ISO 7731 further elaborates that varying fundamental frequencies should be should be selected and that specifically, fundamental frequency sweeps in the range of 500 Hz to 1000 Hz, with four harmonics, will give adequate signal audibility.

In the selection of the frequencies for multi-tone danger signals, several factors should be considered. The frequencies selected should have low attenuation with distance, should correspond to dips in the sound reduction index of windows so that the signal can be heard inside of dwellings and vehicles and should be chosen to convey urgency.

3.5. Ideal Tsunami Danger Signal Design

3.5.1. Frequency components

Based on the discussion of Section 3.4, the tsunami danger signal should have the following frequency composition:

1. 225 Hz increasing in time to 355 Hz. This range was chosen take advantage of the low sound reduction index of windows as described in Section 3.1.2.
2. 500 Hz plus three harmonics increasing with time to 1000 Hz as recommended by ISO 7731.
3. 3000 Hz increasing to 4000 Hz to impress the sense of urgency as described in Section 3.3.

3.5.2. Signal shape

The signal shape should incorporate a change in level with respect to time. Changes in sound level are useful for drawing a listener's attention, and the greater the rate of change, the more demanding the sound [1]. Furthermore, a signal that starts a lower magnitude and then increases is less likely to cause a startle reaction.

Based on the example signals described Patterson and Mayfield [1], the basic pulse used for the danger signal will have rounded onsets and offsets as shown in Figure 6.

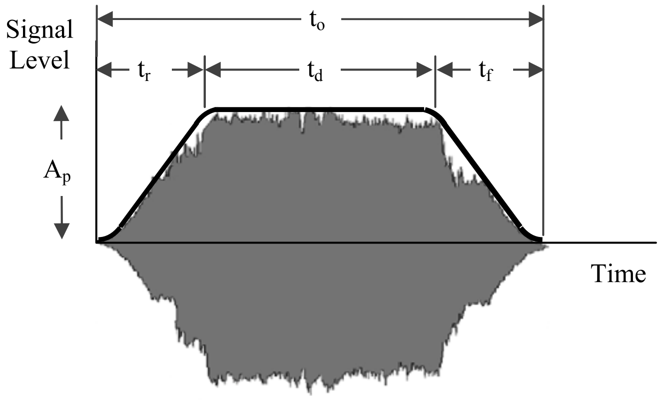

Figure 6: Pulse of the Patterson warning signal

The pulse contains all of the spectral information of the warning sound and is never altered. The figure shows the envelope of the pulse ramps up to the maximum level A_p and remains at that level for a time t_d before ramping back down to zero. The pulse burst is created from a number of these pulses as shown in Figure 7.

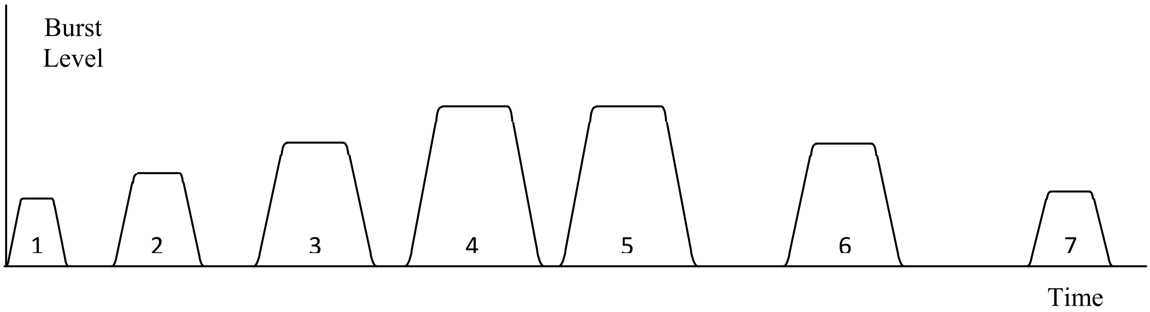

Figure 7: Burst of seven pulses. The height of the pulse signifies the maximum signal level of the pulse. The width of the pulse signifies the duration of the pulse.

The height of each pulse in the figure indicates the level of the pulse and the width indicates the duration. The figure shows that the magnitude of the pulses increases from pulse 1 to pulse 4. The low level at the start of the burst helps to reduce the risk of creating a startle reflex. The duration between pulses 1 and 5 is shown to decrease with each successive pulse. This gives the impression that an object is moving forwards rapidly. The time between pulses increases between pulse 5 and pulse 6 and then pulse 6 and pulse 7 to give the impression that an object is receding slowly. This apparent motion draws attention to the warning signal.

The pulse burst shown in Figure 7 is repeated to form the danger signal. The pulse bursts may be interspersed with verbal warnings. The use of pulse bursts, the increasing level and the change in time between pulses make the danger signal unique, convey urgency and avoid startling the listener.

4. Evaluation of the Existing Tsunami Danger Signals

The majority of the tsunami warning signals currently in use in New Zealand were evaluated using the requirements of ISO 7731 and the recommendations from past studies as outlined in Sections 2 and 3 of this report. The evaluation was based on the analysis of MP3 and wav files which were provided for this study (note that sound files were not available for all of the tsunami warning signals). Due to the data compression method and the recording technique and equipment used to create MP3 files, it was expected that there would be some imperfections in the signals used for the analysis. The imperfections can be manifested as noise in the signal, resulting in low magnitude, random peaks in the frequency domain.

For the evaluation, the signals were first viewed in the time domain which shows the amplitude of the signal versus time. For example, consider signal that includes a single frequency component at 50 Hz as shown in Figure 8.

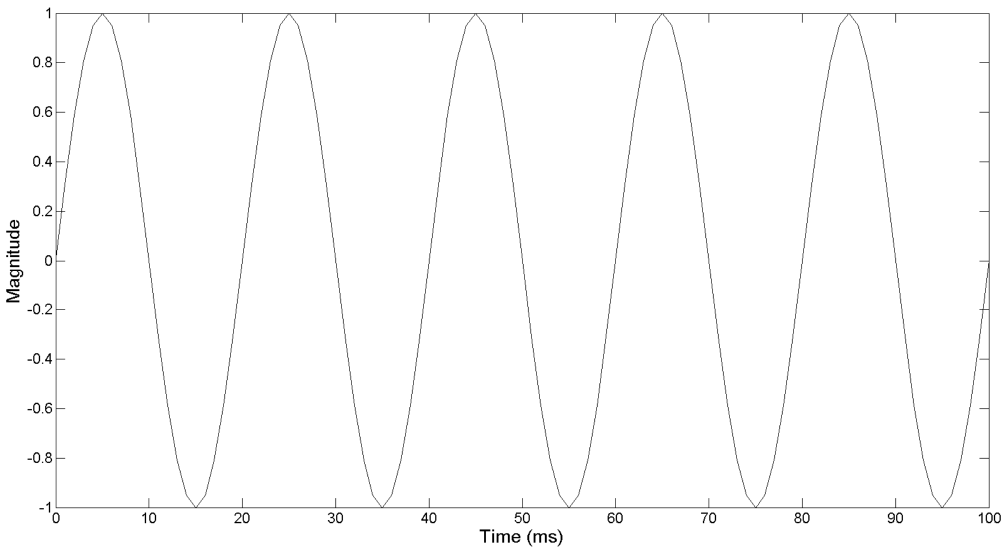

Figure 8: 50 Hz sine wave signal shown in the time domain as amplitude versus time.

Signals shown in the time domain can be used to determine the following:

- Does the signal increase in level over time to convey urgency and to decrease the risk of startling the listener?
- Is the shape of the pulse similar to other signals?
- Is the signal constant or does it pulsate?
- How often does the pulse repeat and what is the duration between the offset of one pulse and the onset of the next?

The spectral characteristics of a signal can be evaluated by viewing the signal in the frequency domain. The frequency domain shows the signal with respect to frequency as shown in Figure 9 for the case of the 50 Hz sine wave.

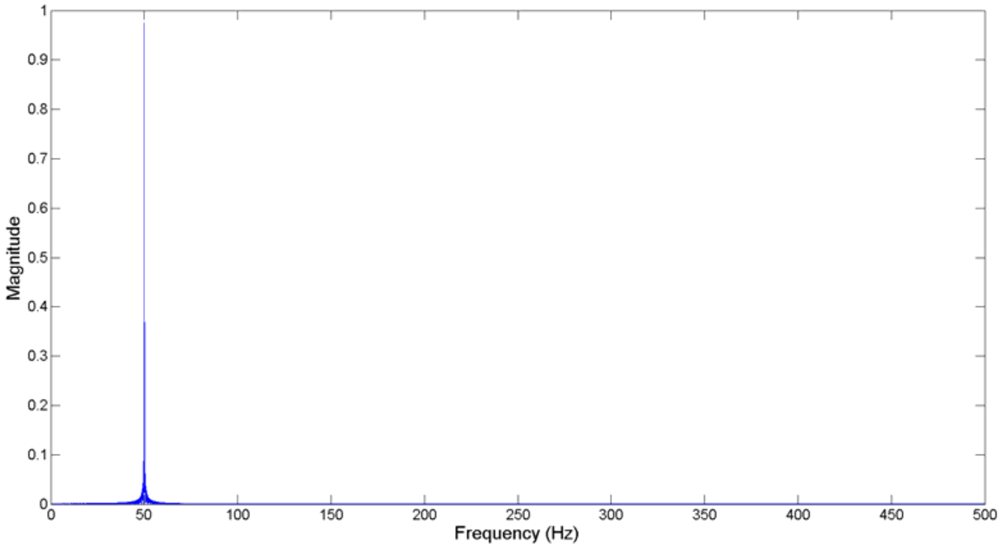

Figure 9: 50 Hz sine wave shown in the frequency domain as magnitude versus frequency.

Signals shown in the frequency domain can be used to determine the following:

- Is the signal single tone (one peak) or multi-tone (more than one peak)?
- How many fundamental tones are included in the signal?
- Are harmonics or inharmonics of the fundamental tones included in the signal?
- Is the majority of the energy of the signals centred at the low frequencies or the high frequencies?

Lastly, the data from the time domain and the frequency domain can be combined to create a waterfall plot as shown in Figure 10.

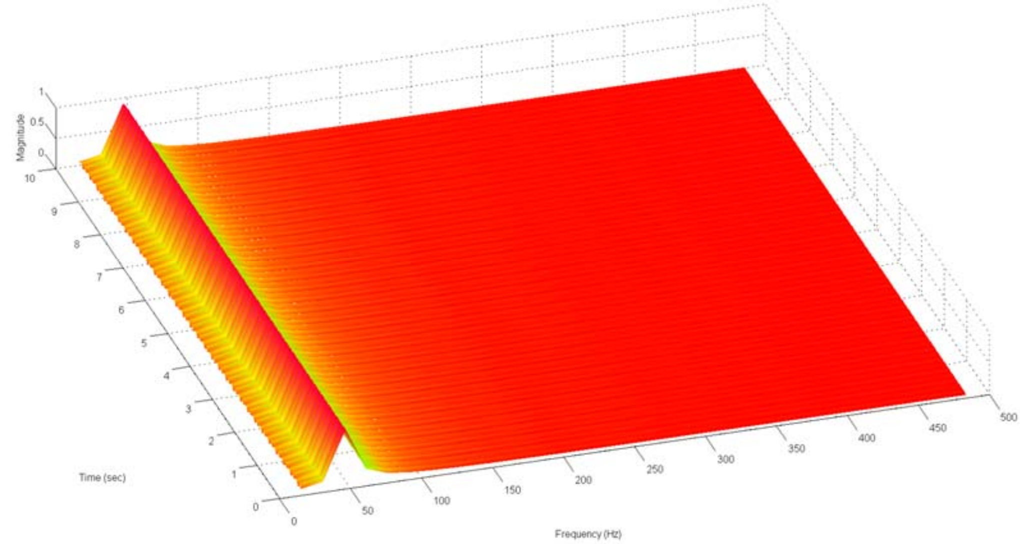

Figure 10: Waterfall plot of the 50 Hz sine wave.

The waterfall plot which was developed from code provided by Irvine [38] shows the frequency plotted along the X axis, the time plotted along the Y axis and the magnitude plotted along the Z axis. The plot shows the frequency spectrum of the signal at each point in time. Figure 10 shows one row of peaks at 50 Hz which extends for the entire length of the signal. If the fundamental frequency were to change with time, the figure would show the peak shifting along the X axis (frequency) with respect to time. Since the row of peaks in the figure is a straight line, the figure indicates the fundamental frequency of the signal did not change with respect to time.

4.1. Fire Siren

ISO 7731 requires that a danger signal be unambiguous and distinct from other signals in use. A common danger signal in use in New Zealand is the fire siren. The fire siren has been analyzed for frequency content to ensure that tsunami danger signal is not identical.

The fire siren was obtained as an MP3 file from the New Zealand Fire Service website [39]. The signal is shown in the time domain in Figure 11.

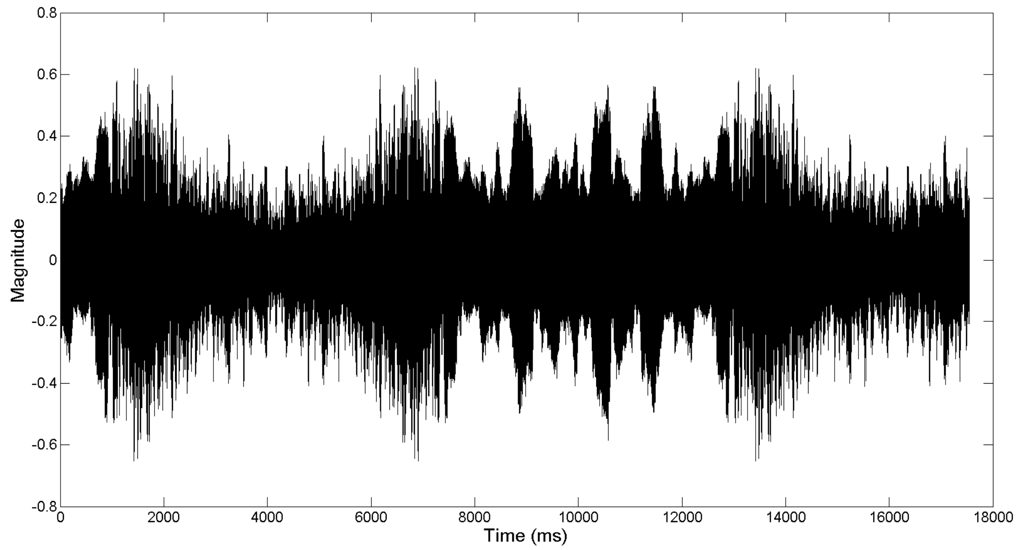

Figure 11: Fire siren shown as magnitude versus time.

The signal is a pulse which is repeated approximately every 5.1 seconds. Note the distortions in the signal between 8000 ms and 12000 ms. It is unknown if the distortions are part of the signal, errors due to the recording method or imperfections in the MP3 file. The fire siren is shown in the frequency domain in Figure 12.

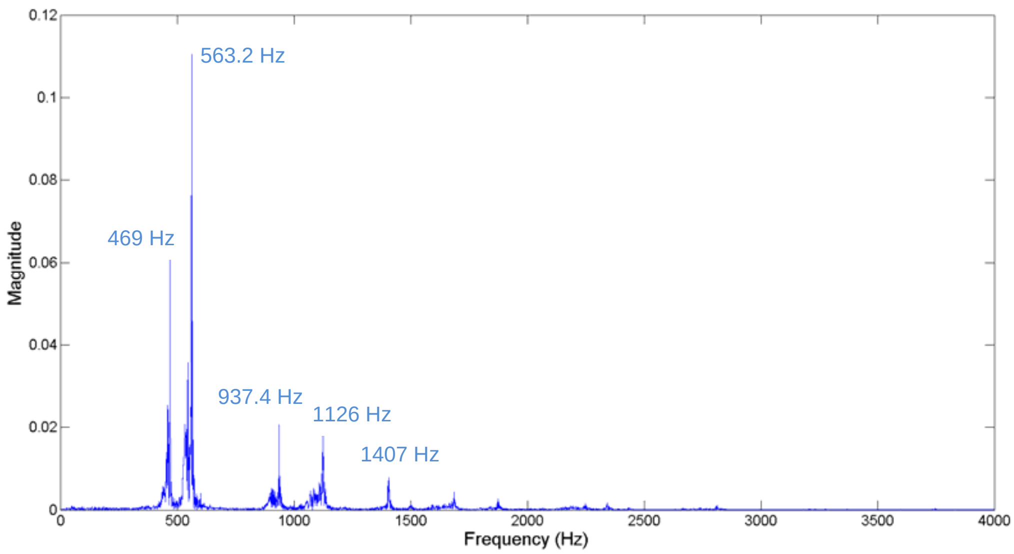

Figure 12: Fire siren shown in the frequency domain as magnitude versus frequency.

The figure shows that the fire signal has a dominant frequency component of 563.2 Hz. The figure also shows a second peak at 469 Hz. Higher frequency peaks such as those shown at 937.4 Hz and 1126 Hz are harmonics of the 469 Hz and 563.2 Hz peaks, respectively.

Harmonics are integer multiples of the fundamental frequencies. A waterfall plot of the fire siren is shown in Figure 13.

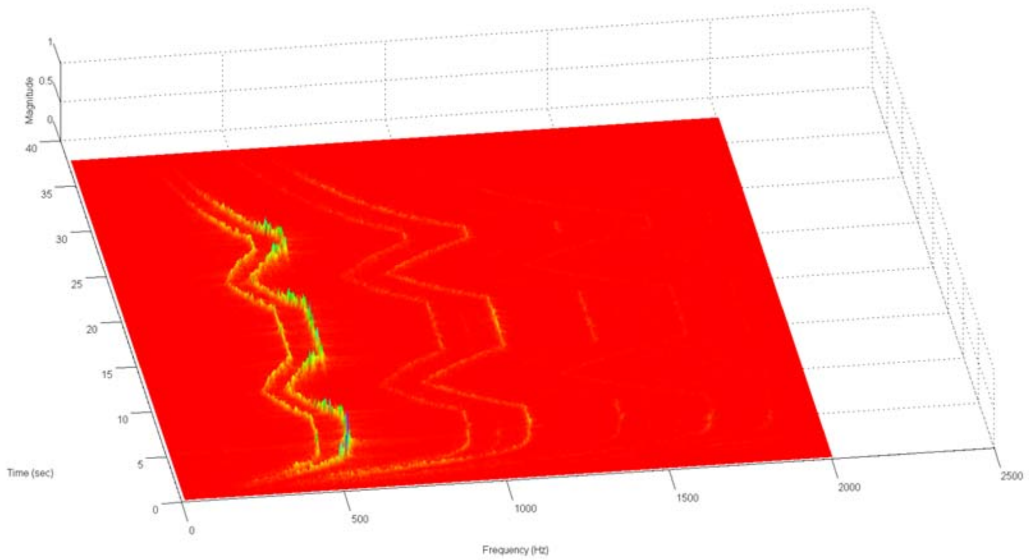

Figure 13: Waterfall plot of the fire siren.

The figure shows the two fundamental tones and their first harmonics vary in frequency with respect to time. As the signal level increases and decreases with time, so does the frequency of the fundamental tones.

To avoid any confusion about the nature of the tsunami warning signal, the use of single or two-tone tsunami danger signals with a fundamental frequency of 469 or 560 Hz should be avoided.

4.2. Sting Signal

The sting signal is a single, repeated pulse as shown in Figure 14.

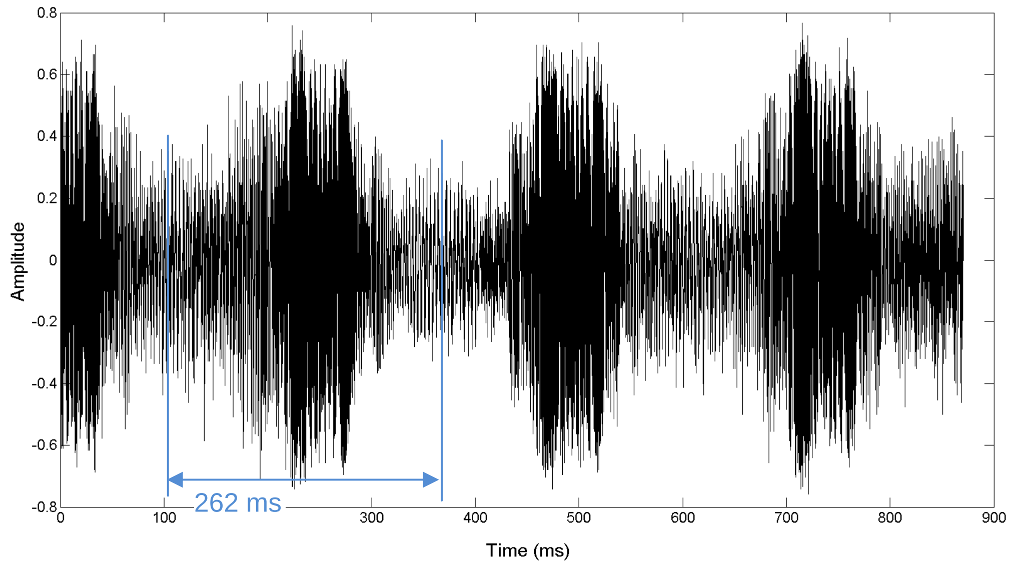

Figure 14: The sting signal in the time domain.

The duration of the pulse is approximately 262 ms (3.8 Hz) as shown in the figure. The rapid pulse rate of 262 ms may result in a signal which is perceived as a continuous signal in built up areas where reverberation due to structures and trees will smooth out the signal. This effect will be made worse by multiple sirens being located in close proximity.

The frequency content of the sting signal is shown in Figure 15.

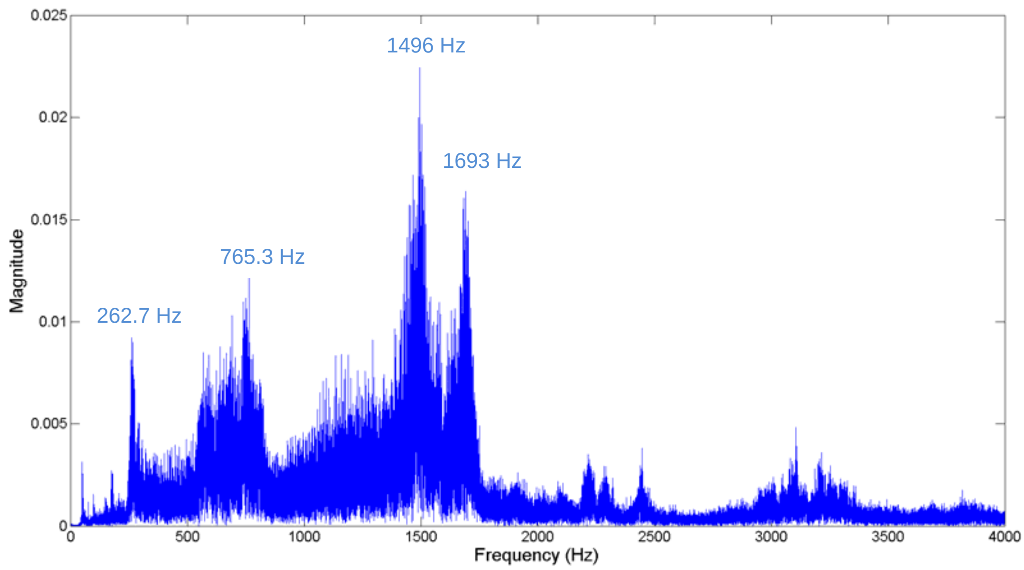

Figure 15: The sting signal in the frequency domain.

The figure shows the dominant frequency components of the sting signal are below 1750 Hz with harmonics above 2000 Hz. The dominant peaks in the spectrum are around 262 Hz, 765 Hz, 1496 Hz and 1689 Hz. The sting signal is therefore a multi-tone signal.

A waterfall plot showing the changes in frequency with respect to time for the sting signal is shown in Figure 16.

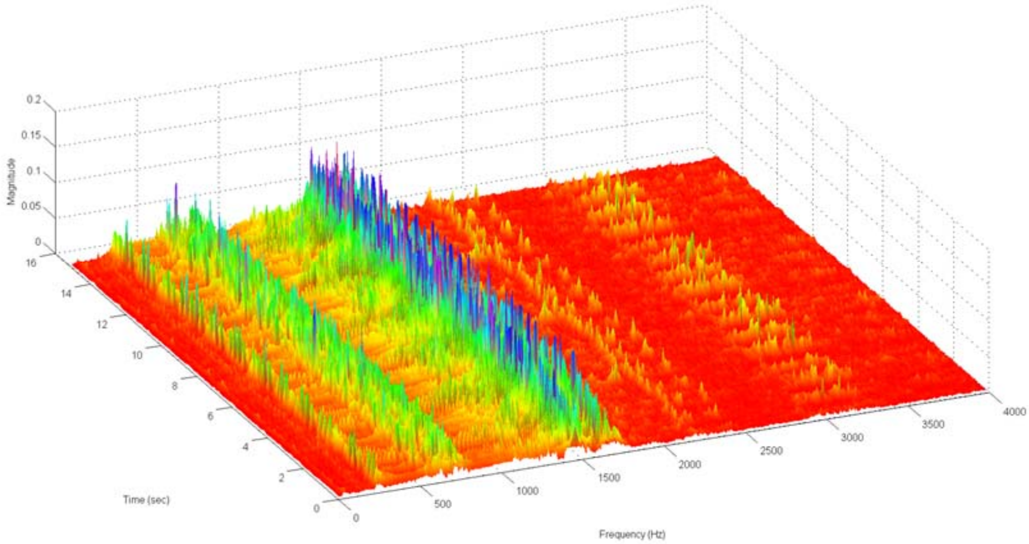

Figure 16: Waterfall plot of the sting signal.

The waterfall plot shows that although the magnitude of the peaks in the frequency domain change with respect to time, the frequency components do not vary with time.

The sting signal failed to meet several of the requirements of ISO 7731. One problem is the similarity between the basic signal form and other emergency signals including emergency vehicle sirens. For example, a fire engine siren from the New Zealand Fire Service website [39] was evaluated as shown in Figure 19 and Figure 20.

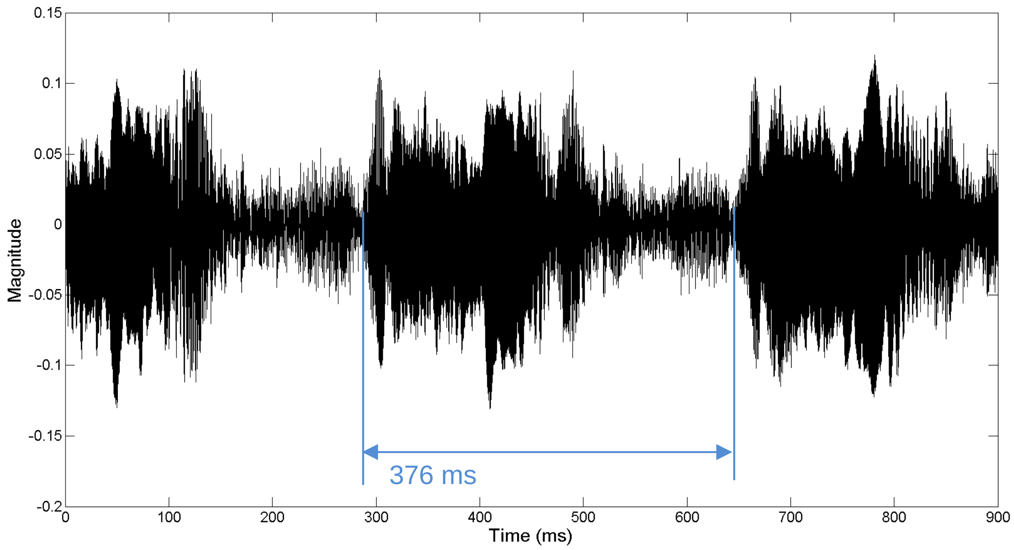

Figure 17: Fire engine signal in the time domain.

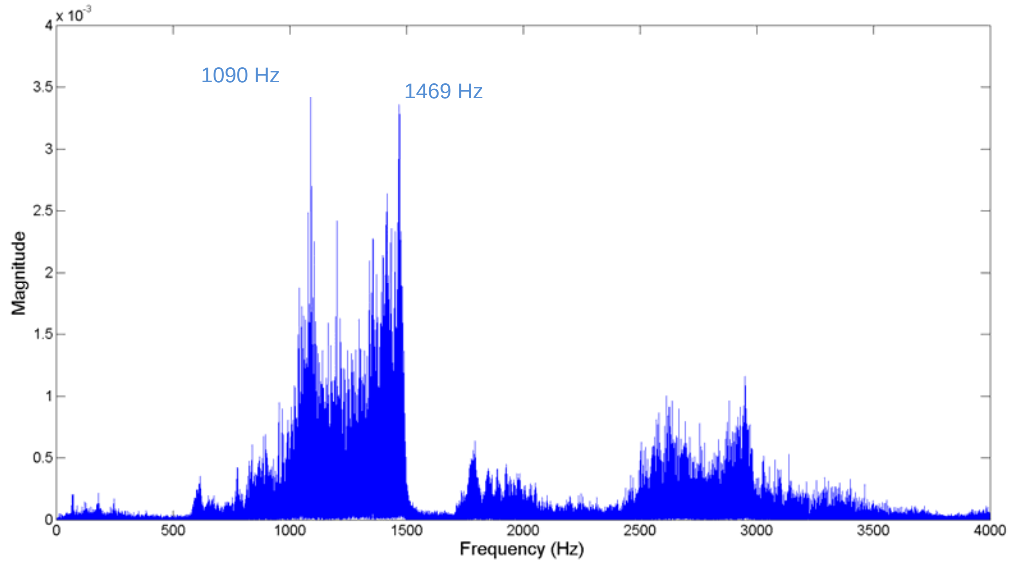

Figure 18: Fire engine signal in the frequency domain.

Although the fire engine signal has a longer duration of 376 ms between pulses, the sting signal and the fire engine signal both have large frequency components around 1460 Hz. Based on the similarities between the signals in terms of signal shape and frequency content, there is a risk that the sting signal could be misinterpreted.

The properties of the sting signal are compared to the requirements and recommendations of Section 3 in Table 1.

Report Section	Requirement / Recommendation	Result	Comment
3.3	Distinctiveness: the signal shall stand out from all other sounds and any other signals	Fail	The sting signal does not meet this requirement. The sting is similar to other sirens such as the fire engine siren.
3.4	Unambiguity: the meaning of the danger signal shall be clear	Fail	The sting signal does not meet this requirement. It is similar to other sirens. There is a risk that the sting may be misinterpreted.
3.6	Include two frequency components in the 500 Hz to 2500 Hz range.	Pass	The sting signal meets this requirement.
3.6.2	Sufficient energy below 1500 Hz for people with hearing loss	Pass	The sting signal meets this requirement.
3.7.2	Pulsating danger signals should be preferred to signals that are constant in time. The repetition shall be between .25 s and 2 s.	Pass	The sting signal has pulsates with a repetition rate of 0.262 s. However, there is a risk that scattering and absorption around the siren will result in a signal that sounds like a non-pulsating sound.
3.7.3	Varying fundamental frequencies should be selected	Fail	The fundamental frequencies do not change with time.
4.1.1	Inclusion of low frequency components for better coverage	Pass	The sting includes a component at 263 Hz. However, there is less energy at this frequency than at other frequencies.
4.1.2	Component between 224 Hz and 355 Hz for transmission through windows.	Pass	The sting includes a component at 263 Hz. However, there is less energy at this frequency than at other frequencies.
4.3	Conveyance of urgency	Maybe	There is no delay between pulses which helps to convey urgency. However, there are no high frequency components or upward sweeping frequency content.

Table 1: Evaluation of the sting signal

The table shows that the sting signal failed to be distinctive, unambiguous and to vary in frequency. Furthermore, the rapid pulse rate risks that the signal will be smoothed out over distance due to reverberation so that the pulsating tone may be heard as a continuous tone.

4.3. Northland Signal

The signal used in Northland is a repeated pulse which increases in level up to a set magnitude. The signal is shown in the time domain in Figure 19.

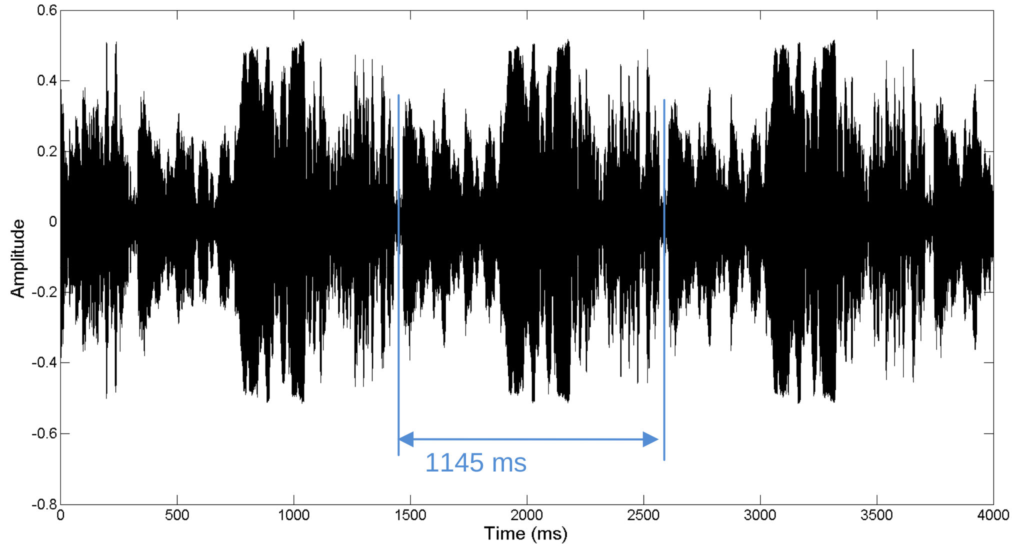

Figure 19: Northland signal in the time domain.

The signal is shown to have a repetition rate of approximately 1145 ms (0.87 Hz). The Northland signal is shown in the frequency domain in Figure 20.

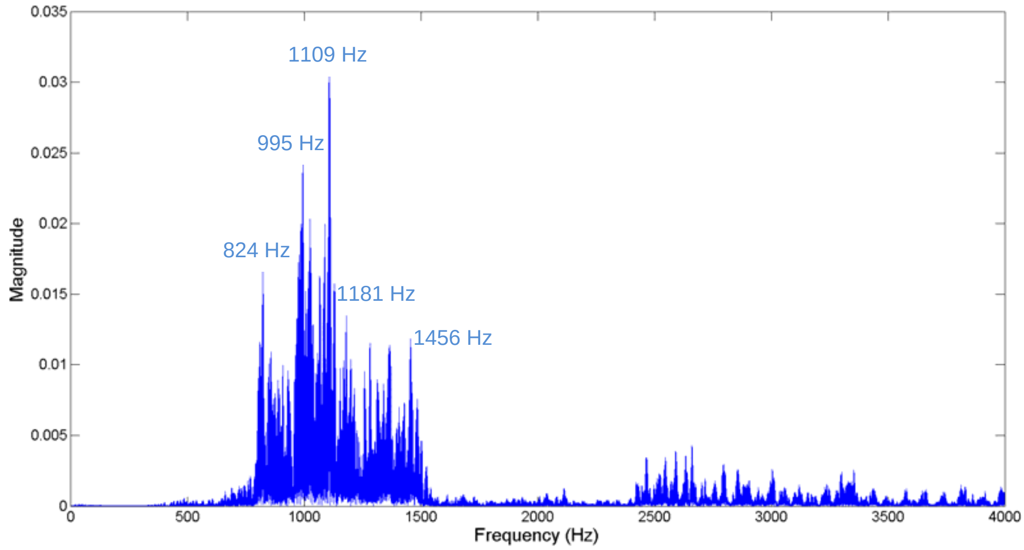

Figure 20: Northland signal in the frequency domain.

The figure shows a grouping of peaks between 800 Hz and 1500 Hz with the highest peak at 1109 Hz. However, at any one time, there is only one fundamental frequency which is varying with time as shown in the waterfall plot in Figure 21.

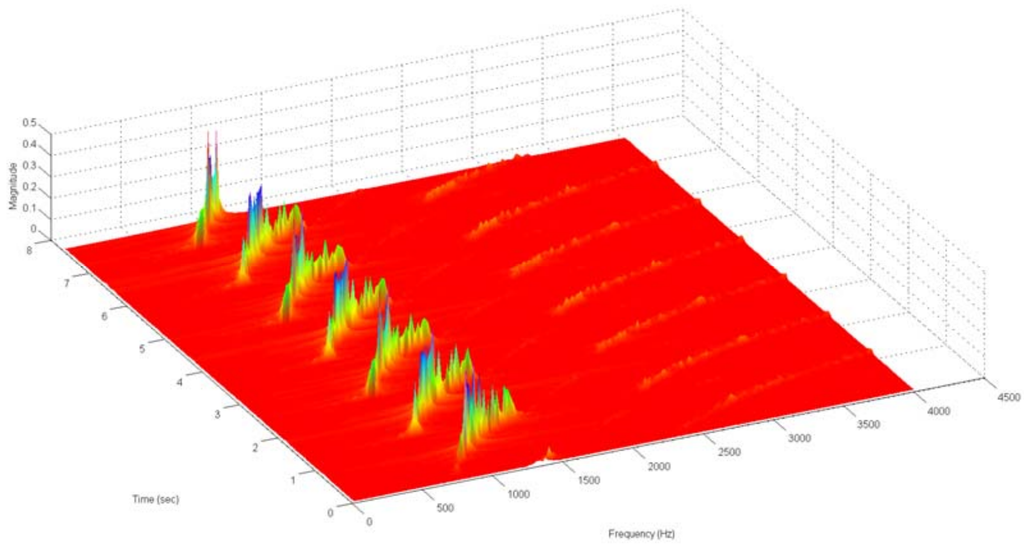

Figure 21: Waterfall plot of the Northland signal.

The Northland signal pulse starts with a fundamental tone at approximately 824 Hz which then increases with respect to time up to approximately 1456 Hz. The rate of change of frequency with time increases with time, resulting in the curved traces shown in the figure. The use of both a frequency sweep and an increasing rate of change of frequency with respect to time coveys urgency and makes the Northland signal distinct. However, the waterfall plot shows that there is only one tone involved in the frequency sweep rather than the two tones ISO 7731 requires. Furthermore, the signal has no energy in the low frequencies where energy is needed for the transmission of the signal through windows.

The properties of the Northland signal are further compared to the requirements and recommendations of Section 3 in Table 1.

Report Section	Requirement / Recommendation	Result	Comment
3.3	Distinctiveness: the signal shall stand out from all other sounds and any other signals	Pass	The Northland signal has a ramped shape which makes it distinctive.
3.4	Unambiguity: the meaning of the danger signal shall be clear	Pass	The Northland signal has a ramped shape which makes it distinctive from other sounds and other emergency signals.
3.6	Include two frequency components in the 500 Hz to 2500 Hz range.	Fail	There is one fundamental frequency which varies with time.
3.6.2	Sufficient energy below 1500 Hz for people with hearing loss	Pass	The energy is between 800 Hz and 1500 Hz.
3.7.2	Pulsating danger signals should be preferred to signals that are constant in time. The repetition shall be between .25 s and 2 s.	Pass	The repetition rate is 1.15 seconds.
3.7.3	Varying fundamental frequencies should be selected	Pass	The waterfall plot shows the fundamental frequencies vary with respect to time.
4.1.1	Inclusion of low frequency components for better coverage	Fail	The energy is located only between 800 Hz and 1500 Hz.
4.1.2	Component between 224 Hz and 355 Hz for transmission through windows.	Fail	There are no peaks in this frequency range.
4.3	Conveyance of urgency	Pass	The Northland signal increases in pitch over time, conveying urgency. There is a short duration between pulses which also conveys urgency.

Table 2: Evaluation of the sting signal

Due to the lack of a second, low frequency tone, the Northland signal is not recommended. However, if the signal can be modified to include a second tone which varies with time between 224 Hz and 355 Hz, the signal would meet all of the requirements.

4.4. Auckland Signals

Three different signals are used in Auckland, each to convey a different meanings as shown in Figure 22.

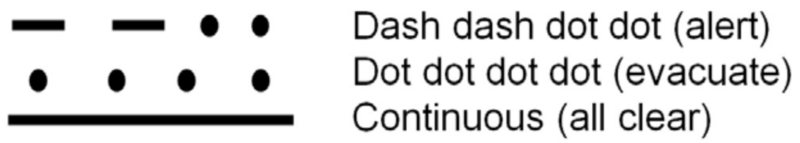

Figure 22: The three signals used in Auckland and their meanings from Morris [6].

4.4.1. Auckland Alert Signal

The alert signal is shown in the time domain in Figure 23

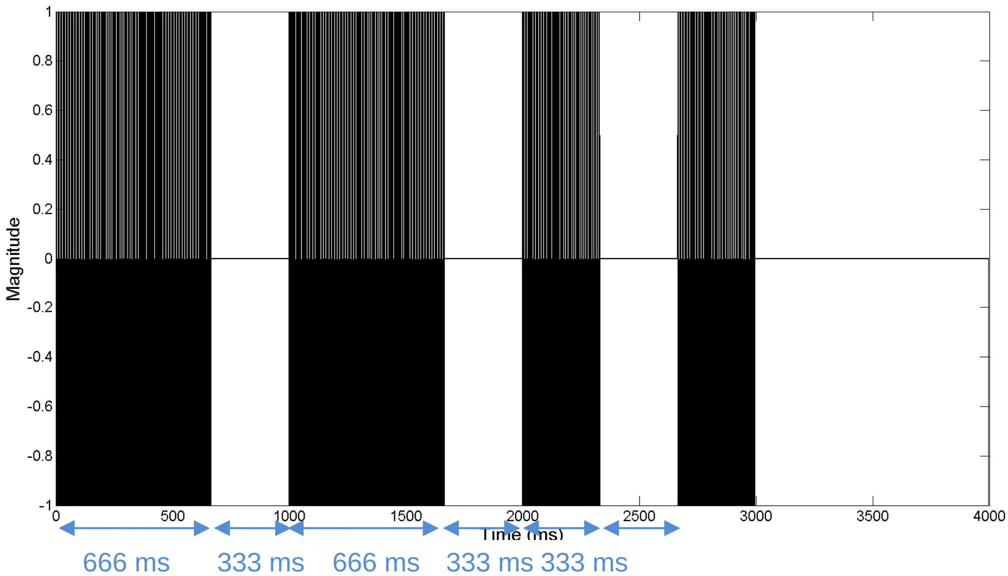

Figure 23: The Auckland alert signal in the time domain.

The Auckland alert signal has a pattern of two long pulses followed by two short pulses. The duration between pulses is shown to be 333 ms. The signal is shown in the frequency domain in Figure 24.

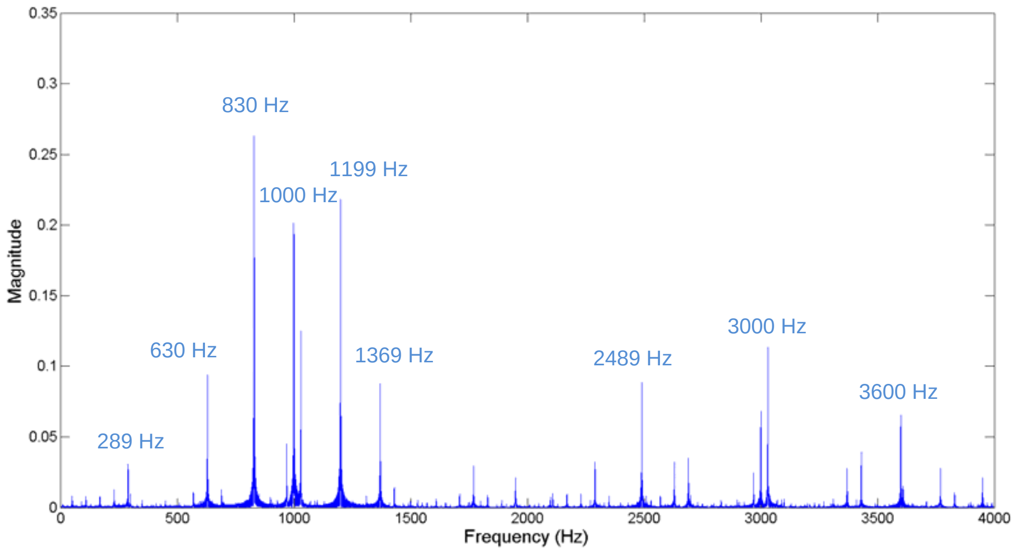

Figure 24: The Auckland alert signal in the time domain.

The figure shows frequency content up to 4000 Hz. The peaks above 1500 Hz are harmonics. A waterfall plot of the Auckland alert signal is shown in Figure 25.

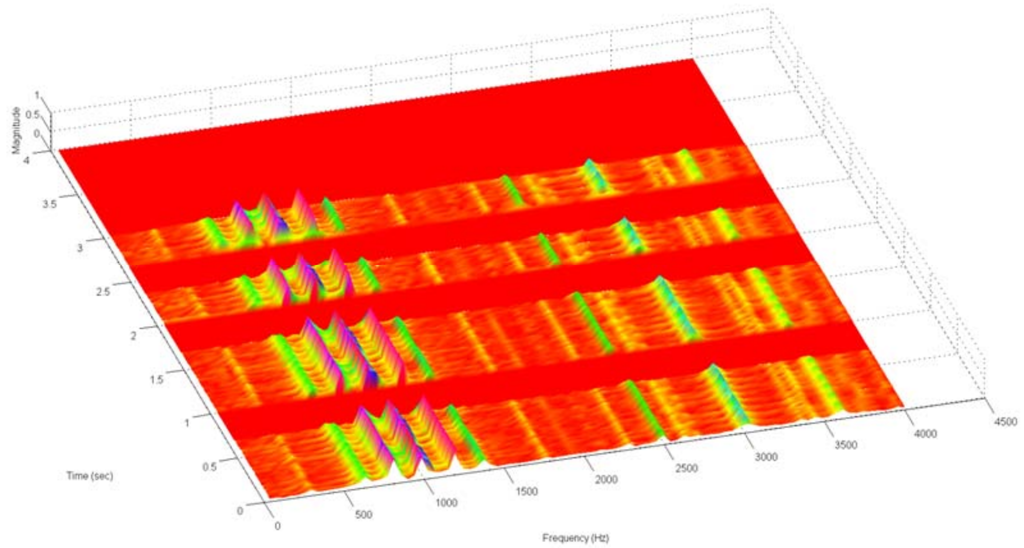

Figure 25: Waterfall plot of the Auckland alert signal.

The waterfall plot shows that the frequency components of the signal do not vary with respect to time.

4.4.2. Auckland Evacuate Signal

The evacuate signal is shown in the time domain in Figure 26.

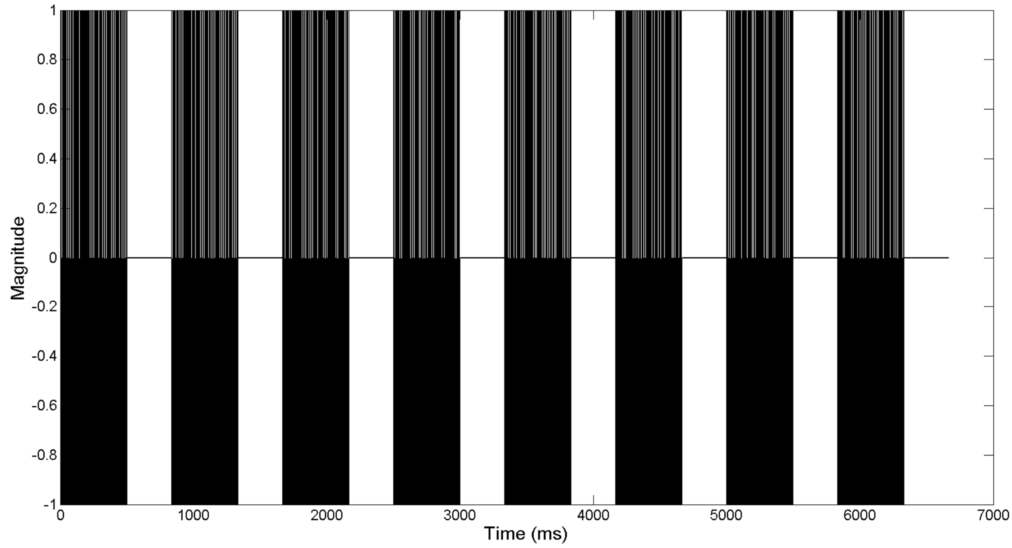

Figure 26: The Auckland evacuate signal in the time domain.

Each tone shown in the figure is 500 ms long and there is a delay of 333 ms between tones. The frequency content is the same as the Auckland alert tone as shown in Figure 24.

4.4.3. Auckland All Clear Signal

The all clear signal is shown in the time domain in Figure 27.

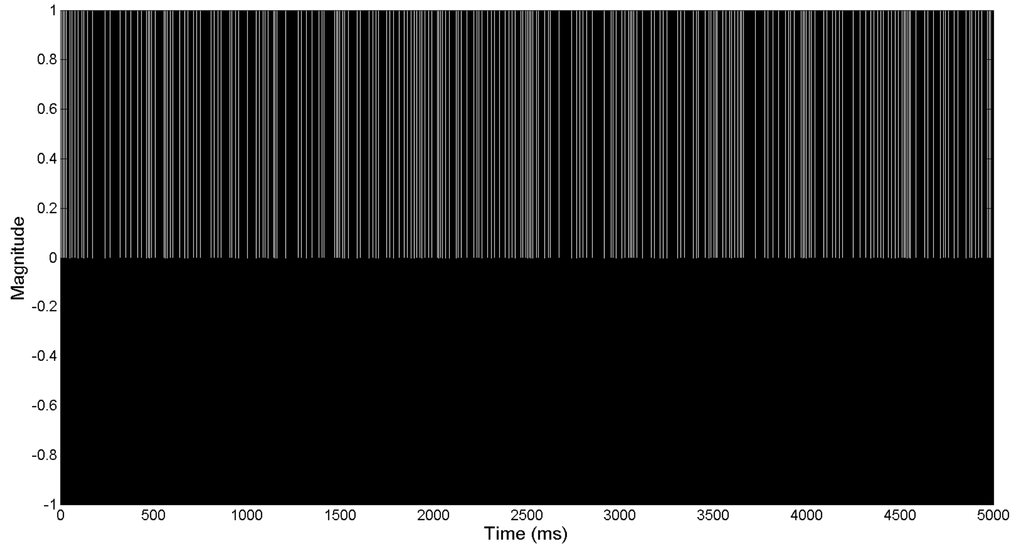

Figure 27: The Auckland evacuate signal in the time domain.

The all clear signal is one long tone with the same frequency content as the Auckland alert tone as shown in Figure 24.

4.4.4. Auckland Signals Evaluation

The use of three signals, each using the same frequency content, but with different pulse lengths and delays risks a lack of distinction between the signals. There is the potential for people to confuse the signals or worse to result in people taking the wrong actions. For example, a study by Johnston, *et al*. [40] investigated people's understanding of tsunami hazards on the Washington coast, their knowledge regarding the Washington State tsunami warning system and their preparedness to deal with tsunami activity. The study identified that the residents have to negotiate a highly complex decision making process to figure out whether to respond, and how to respond, to a warning. A combination of their inadequate knowledge and the fact that the effect of tsunami depends on so many different factors, resulted in participants being highly unsure with regard to how to make these decisions, particularly within the short time frame available within which to make these decisions. This is why studies such as that by Gregg, *et al*. [18] recommend a single tsunami danger signal that alerts the at-risk people to evacuate to an area or to learn more about the emergency situation at hand. The greater the ambiguity regarding interpretation of a warning, the greater the likely delay in public response. Therefore, the use of different signals, all with the same frequency components and only differentiated by the pulse duration and the time between pulses is not recommended.

The Auckland signals have a sudden onset instead of a ramping up of the intensity level which is likely to cause a startle response and therefore the signals are unacceptable in terms of the requirements for a danger signal. Further evaluation of the Auckland signals is shown in Table 3.

Report Section	Requirement / Recommendation	Result	Comment
3.3	Distinctiveness: the signal shall stand out from all other sounds and any other signals	Fail	The frequency components and the temporal characteristics of the Auckland signals are distinct from other signals, but all three signals have identical frequency components and are therefore not distinct.
3.4	Unambiguity: the meaning of the danger signal shall be clear	Fail	The use of three signals to convey different meanings risks the misunderstanding of the signals by the people in the coverage area.
3.6	Include two frequency components in the 500 Hz to 2500 Hz range.	Pass	The Auckland signals have distinct frequency components between 500 Hz and 2500 Hz.
3.6.2	Sufficient energy below 1500 Hz for people with hearing loss	Pass	There are distinct peaks below 1500 Hz
3.7.2	Pulsating danger signals should be preferred to signals that are constant in time. The repetition shall be between .25 s and 2 s.	Pass	The alert and evacuate signals are pulsating.
3.7.3	Varying fundamental frequencies should be selected	Fail	The frequencies are consistent with time.
4.1.1	Inclusion of low frequency components for better coverage	Fail	The energy is predominately between 600 Hz and 1500 Hz.
4.1.2	Component between 224 Hz and 355 Hz for transmission through windows.	Fail	There is little energy in this range.
4.3	Conveyance of urgency	Fail	The signal was not designed to convey urgency.

Table 3: Evaluation of the Auckland signals

In summary, the Auckland signals, both individually and as a group failed to meet the requirements and recommendations for a danger signal.

4.5. Christchurch Signal

The signal used in Christchurch is the Auckland evacuate signal as shown in Figure 24 and Figure 26. Although by itself, the evacuate signal is distinctive, the evacuate signal fails to meet the requirements and recommendations for a danger signal as shown in Table 4.

Report Section	Requirement / Recommendation	Result	Comment
3.3	Distinctiveness: the signal shall stand out from all other sounds and any other signals	Pass	The evacuate signal is distinctive from other sounds and sirens.
3.4	Unambiguity: the meaning of the danger signal shall be clear	Pass	The evacuate signal is distinctive.
3.6	Include two frequency components in the 500 Hz to 2500 Hz range.	Pass	The evacuate signal has distinct frequency components between 500 Hz and 2500 Hz.
3.6.2	Sufficient energy below 1500 Hz for people with hearing loss	Pass	There are distinct peaks below 1500 Hz
3.7.2	Pulsating danger signals should be preferred to signals that are constant in time. The repetition shall be between .25 s and 2 s.	Pass	The evacuate signal is pulsating.
3.7.3	Varying fundamental frequencies should be selected	Fail	The frequencies are consistent with time.
4.1.1	Inclusion of low frequency components for better coverage	Fail	The energy is predominately between 600 Hz and 1500 Hz.
4.1.2	Component between 224 Hz and 355 Hz for transmission through windows.	Fail	There is little energy in this range.
4.3	Conveyance of urgency	Fail	The signal was not designed to convey urgency.

Table 4: Evaluation of the Christchurch evacuate signal

Due to the problems outlined in the table, the Christchurch evacuate signal is not recommended.

4.6. Thames Coromandel Signal

The signal used in Thames Coromandel is produced by a mechanical siren. Once the siren is turned on, the signal level increases until it becomes a steady tone at the full level the siren can produce as shown in Figure 28.

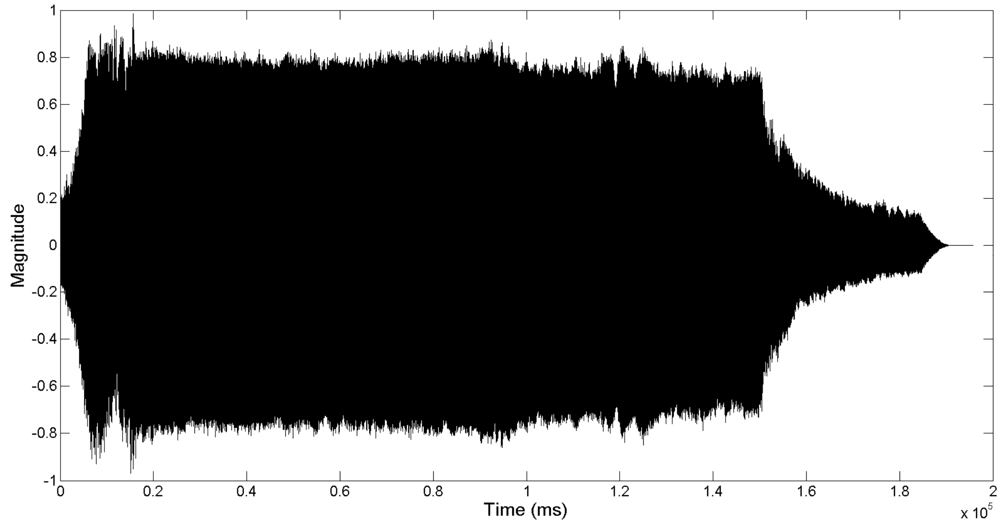

Figure 28: Thames Coromandel signal in the time domain.

At the end of the signal length, the level exponentially decays until the siren turns off. The signal is shown in the frequency domain in Figure 29.

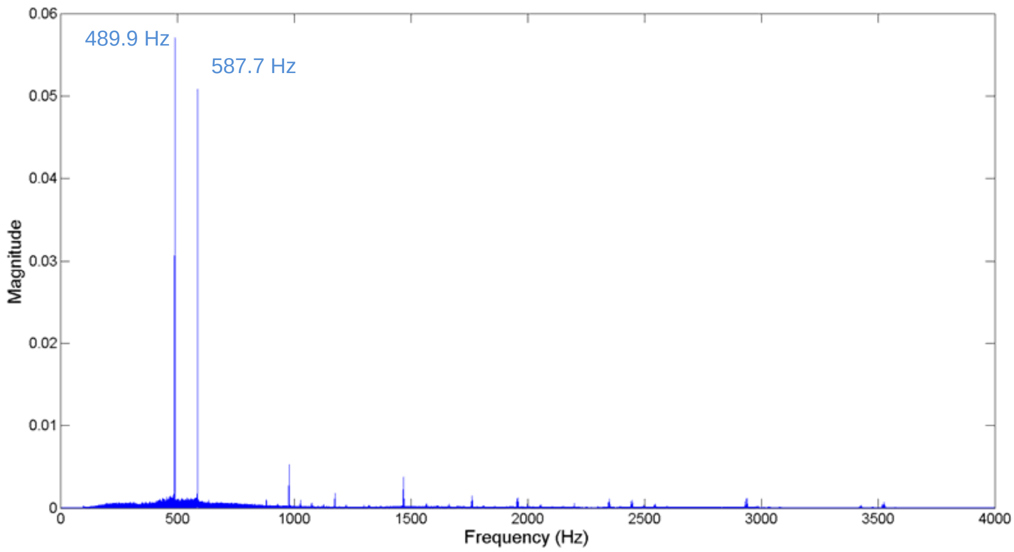

Figure 29: Thames Coromandel signal in the time domain.

The figure shows that the signal has two frequency components, one at 489.9 Hz and one at 587.7 Hz. However, other mechanical sirens used in New Zealand may have other frequency components. The waterfall plot of the signal is shown Figure 30.

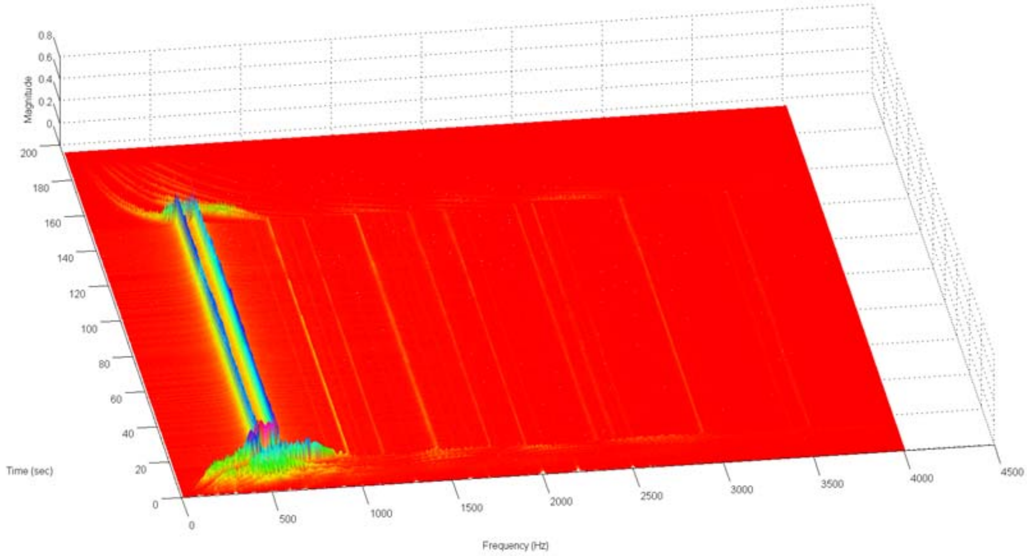

Figure 30: Waterfall plot of the Thames Coromandel signal.

The waterfall plot shows that the fundamental frequencies to change at when the signal is turned on and off. However, for most of the duration of the signal, the frequency components do not vary and the signal is a continuous tone. The use of a continuous tone has been described as ineffective as an attention getting device and ISO 7731 states that pulsating signals are preferred over continuous tone signals.

The Thames Coromandel signal is reviewed in Table 5.

Report Section	Requirement / Recommendation	Result	Comment
3.3	Distinctiveness: the signal shall stand out from all other sounds and any other signals	Pass	The signal is different than other signals including the fire signal.
3.4	Unambiguity: the meaning of the danger signal shall be clear	Pass	Studies [37] have shown that sirens have an association to danger or threat.
3.6	Include two frequency components in the 500 Hz to 2500 Hz range.	Fail	Although the signal does include two frequency components, they are similar in frequency and therefore are more likely to be masked by other sounds than two components spread further apart.
3.6.2	Sufficient energy below 1500 Hz for people with hearing loss	Pass	The frequency components are below 1500 Hz.
3.7.2	Pulsating danger signals should be preferred to signals that are constant in time. The repetition shall be between .25 s and 2 s.	Fail	Once the signal is ramped up to full level, the signal remains constant for three minutes.
3.7.3	Varying fundamental frequencies should be selected	Fail	Although the frequencies to vary at the start and end of the signal, the fundamental frequencies do not vary for the majority of the signal duration.
4.1.1	Inclusion of low frequency components for better coverage	Pass	The frequency components at 500 Hz will be sufficient
4.1.2	Component between 224 Hz and 355 Hz for transmission through windows.	Fail	No energy in the idea frequency range for transmission through windows.
4.3	Conveyance of urgency	Pass	The rising level at the start of the signal conveys loudness and urgency.

Table 5: Evaluation of the Thames Coromandel signals

Although the Thames Coromandel signal is shown to fail many of the requirements for a danger signal, an advantage of the signal is that the signal does convey danger. Lazarus and Höge [3] showed that sirens have an association to danger or threat. Signals similar to the one in Thames Coromandel may be heard on television or other media in association with danger and so people have already created an understanding of the urgency of such a signal.

The siren in use in Thames Coromandel is a mechanical siren. Unlike electronic sirens which can be reprogrammed to produce different signals, the signal produced by the mechanical siren can not be changed to comply with the requirements for a danger signal. Based on the non-compliance of the Thames Coromandel signal and the lack of flexibility to change the signal, further use of mechanical sirens is not recommended.

4.7. Summary

A summary of the evaluation of the dangers signals is shown in Table 6.

Report Section	Requirement / Recommendation	Sting	Northland	Auckland	Christchurch	Thames Coromandel
3.3	Distinctiveness: the signal shall stand out from all other sounds and any other signals	Fail	Pass	Fail	Pass	Pass
3.4	Unambiguity: the meaning of the danger signal shall be clear	Fail	Pass	Fail	Pass	Pass
3.6	Include two frequency components in the 500 Hz to 2500 Hz range.	Pass	Fail	Pass	Pass	Fail
3.6.2	Sufficient energy below 1500 Hz for people with hearing loss	Pass	Pass	Pass	Pass	Pass
3.7.2	Pulsating danger signals should be preferred to signals that are constant in time. The repetition shall be between .25 s and 2 s.	Pass	Pass	Pass	Pass	Fail
3.7.3	Varying fundamental frequencies should be selected	Fail	Pass	Fail	Fail	Fail
4.1.1	Inclusion of low frequency components for better coverage	Pass	Fail	Fail	Fail	Pass
4.1.2	Component between 224 Hz and 355 Hz for transmission through windows.	Pass	Fail	Fail	Fail	Fail
4.3	Conveyance of urgency	Maybe	Pass	Fail	Fail	Pass

Table 6: Summary of the evaluation of the danger signals.

The table shows that none of the signals met all of the requirements and recommendations. Of the signals evaluated, the signal used in Northland met almost all of the requirements of ISO 7731, but failed the recommendations of the standard and the prior studies. In particular, the Northland signal failed to include frequency components at the frequencies which would be best for transmission into houses and vehicles. If the Northland electronic sirens could be reprogrammed to include frequency sweep between 224 Hz and 355 Hz, the Northland signal would be fully compliant with the requirements for a danger signal.

5. Verbal Warnings

The sirens used in New Zealand are either electro-mechanical or fully electronic devices. Both types of sirens produce non-verbal danger signals, but electronic sirens have the advantage that they can also broadcast spoken instructions. Verbal warnings are effective because they are highly redundant in the sense that a speech signal contains more information than necessary for sound identification [37]. Furthermore, verbal warnings may require minimal learning and are suggested to have advantages over non-speech sounds in situations when the information to be conveyed is very complex, when the number of warnings a system is very large or when the user is not required to make a particularly rapid response [41].

Danger signals that do not incorporate spoken instructions are limited in a number of ways. The major limitations of sirens include that people did not pay much attention to them [42] and often do not understand the meaning of different signals. Tones and sounds can alert people of danger, but verbal messages are superior in their ability to inform and instruct message recipients. Verbal warnings can capture attention and convey information at the same time. Well-designed verbal warnings have immediacy and specificity that make them preferable to sound alarms and this is one reason spoken messages are used so extensively in emergency situations [13]. This is not to say that verbal messages are superior to non-verbal messages. In settings where there is a high level of background noise or low speech intelligibility, people can often be reached more effectively by nonverbal signals than by voice alarms. Furthermore, non-verbal signals are both language independent and have the potential to be understood more efficiently and more rapidly. Therefore, in order to be effective, warning systems in public places should employ “layers” of warning messages- alarm sounds, accompanied by verbalizations that reinforce one another [13].

Two critical factors for a verbal warning message are audibility and intelligibility [10]. Furthermore, effective verbal warnings require clear, concise and consistent messages with redundancy and give specific advice on what the effect will be and what to do to reduce the risk from the impending hazard event [43]. Darienzo, *et al.* [44] recommend that public address should ideally be pre recorded to avoid potential problems with unintelligible messages from a stressed system operator.

The style and content of a message can have a dramatic effect on public response. Sufficient research has been conducted to discern a poor message from a good one and even a good one from one that reflects state-of-the-art practices. Five specific topics that are important to include in assembling the actual content of a public warning message are the nature, location, guidance, time, and source of the hazard or risk [42].

Specific guidance for verbal communication is given in ISO 9921 [8]. Guidance specifically for vocal signals for older adults can be found in McLaughlin and Mayhorn [12]. Lastly, a report by Mileti and Sorensen [45] for the U.S. Department of Energy includes a number of recommendations for effective emergency verbal warnings.

6. Sirens

An example of the fixed electronic horn-speaker currently in use in New Zealand is shown in Figure 31.

Figure 31: Example of a siren installed in Northland. Image from the Northland Regional Council website [46].

Electronic horn-speakers are used because they are capable of producing high signal noise levels, but at the expense of an uneven frequency response. Horns typically have a cut off frequency below which their response drops off. Therefore, horns are most often used for midrange and high frequencies. The horn itself can act as a directional control device to guide the airborne acoustic energy into particular directions or regions [47]. The acoustic directivity of the siren will all have an effect upon the transmission of the sound from the siren to the coverage area [2].

A common practice in New Zealand is to create omni-directional sound sources by arranging the horn-speakers in arrays as shown in Figure 32.

Figure 32: Array of horn-speakers to create an omni-directional array.

Omni-directional sirens provide greater area coverage than do rotating or directional sirens. They provide a more constant signal that improves public alerting in areas with highly fluctuating ambient noise, along with the reinforcing effect of multiple sound sources (up to a 3 dB increase for two adjacent sound sources in the same environmental setting) [10].

Therefore omni-directional sirens can be used to good advantage in areas with high population density, areas with high ambient noise levels (e.g., near factories, highways, or airports), and to cover "pockets" between directional sirens, particularly for partially hilly to hilly terrains. However, use of all omni-directional devices may not be desirable for all situations, particularly for voice address in areas where buildings and terrain features may cause echoes [10].

7. Siren Installations

The best places for sirens to be installed are near areas that have high ambient noise (e.g., highways, railroads, and commercial areas) [10]. The density of the sirens must be sufficient for effective coverage of the area receiving the danger signal while maintaining the requirements for signal level as specified in ISO 7731.

The mounting of the tsunami warning sirens plays an important role in the detection and understanding of the danger signal by the people in the coverage area [2]. In general, this requirement can be achieved by mounting the device high enough above ground level so that the sound is directed mostly over the heads of people standing on the ground near the device. The minimum mounting height needed to meet this requirement, as calculated for a device rated at 120 dB, should be 10 m above the ground. Of course, a higher mounting may be desirable to place the source above the prevailing rooftop height [10]. This will allow the sound to propagate over buildings.

Furthermore, devices with greater effective ranges generally require higher mounting height to ensure that nearby pedestrians do not receive harmful noise exposure. It is also important that the sirens are not mounted so high that they exceed the capacity of available equipment required to service them (bucket trucks). Also, louder devices do not always correlate to greater intelligibility, particularly in environments such as urban areas that may be prone to echoes [10].

Once sirens are installed, the signal level of the siren may be determined *in situ* using the measurement procedure detailed the standard, ANSI S12.14-1992 [48].

Further guidance for the location of sirens can be found in the *Outdoor Warning Systems: Technical Bulletin (Version 2.0)*, published by FEMA [10].

8. Periodic Review of the Warning System

Since the frequency of tsunamis is small even in tsunami-prone countries, special efforts are required to maintain readiness. This means that continuous readiness training, such as drills or exercises which follow established protocol and procedures for decision-making, response and action are essential [11].

ISO 7731 states that the effectiveness of the danger signal shall be reviewed at both regular intervals and whenever a new signal (whether a danger signal or not) or a change in the ambient noise occurs, or any other relevant changes are made. Such testing should consider receiver characteristics and task characteristics, as well as characteristics of the environment in which the risk communication will occur [12]. In a review of the danger signals used for the Ruapehu Volcano, Leonard, *et al.* [43] stress the importance of annual exercises. For a public notification system to be assured as reliable there must be redundancy, permanently ongoing testing and maintenance and assured backed up power supply. The study noted that even in Baños, Ecuador, a town which was evacuated due to a volcanic eruption in 1999 and which experiences regular ash falls, many deficiencies are discovered in the warning system's effectiveness each time it is exercised.

Evaluation generally takes the form of (a) surveying of risk and response–action perceptions and (b) observations of exercises and blind tests. Without the quantitative and qualitative datasets acquired for Ruapehu, researchers would not have been able to ascertain what was and was not working and what should change in terms of the concept of an optimally effective warning system [43]. Those conducting the evaluation must also clearly establish the criteria for success prior to testing. Success in some situations might be defined as full compliance by at least 95% of the population tested [12].

9. Public Education

Public education is vital for preparing the public to respond properly to tsunami danger signals. An educated public is more likely to take steps to receive tsunami warnings, recognize potentially threatening tsunami events, and respond appropriately to those events [49]. A study by Gregg, *et al*. [18] surveyed people in Hilo, Hawaii, a city which was largely destroyed in a past tsunami, about the meaning of the tsunami warning siren. The study anticipated that the understanding of the siren would be high. However, consistent with other studies, the understanding of the specific meaning of the siren was found to be very low. On average, the correct student and adult responses were about 1% and 13%, respectively.

It is generally assumed by emergency management agencies that warnings will be treated at face value, accepted and acted upon. This assumption is not, however, always justified. For example, recent research on tsunami warnings found that people may choose not to respond to warnings for several reasons, including beliefs regarding the avoidability of the hazard, placing a higher value on reuniting with family, not wishing to appear foolish if they evacuate because of a false alarm, or assuming others will come to their rescue no matter what happens [43]. In another example, when a tornado struck Calhoun County, Alabama in 1994, 88% of the residents in the geographic area for which warning sirens had been provided heard the sirens, but only 31% sought shelter. Researchers of the event concluded that public education is needed in order to ensure that people actually respond appropriately when warnings are issued.

Multiple studies [3, 13, 40, 43-45, 49-56] have emphasized the importance of public education about the meaning and the proper response to the tsunami danger signals. Danger signals, particularly for infrequent events, can create a sense of ambiguity that results in delays as people look to others to clarify the situation and what they should do [18]. The complex nature of tsunami behaviour, and the attendant difficulties in prescribing a course of action in response to specific signs of tsunamis, increases the likelihood of ambiguity during tsunami events [40]. Prior public education can “prime” people for response in some future warning, for example, by educating people about the location of evacuation shelters [45].

Evidence suggests that well-designed public education initiatives increase public hazard knowledge and warning responsiveness. Public education through hazard/evacuation maps, media releases (built upon engagement with the media as a partner), brochures/posters, meetings, internet resources etc. are critical to understanding of warning system details and the range of suitable responses. Public education should at least address who will issue the warning message(s), its content, its timing, and the media used to communicate risk messages. It is also important to include in each message what should be done in response to that warning message [43].

In addition to enhancing hazard knowledge, a second objective of public education programs is to facilitate preparedness to deal with hazard consequences. That is, the degree to which knowledge and awareness translate into preparedness behaviour. An examination of the number of preparedness items adopted suggests that receipt of the hazard and preparedness information did not translate into a corresponding level of preparedness [40].

Thus it is essential to invest in disaster education and training. Investments leading to an increase in social capital will enable communities to cope with disasters of all kinds [51]. Risk communication includes raising public awareness and effecting behavioural change in the areas of mitigation and preparedness; the deployment of stable, reliable, and effective warning systems; and the development of effective messaging for inducing favourable community response to mitigation, preparedness and warning communication [56].

Part of the education program can be to instruct people to get more information and then to visit their neighbours to ensure that everyone in the area is aware of the danger signal. The physical proximity of neighbours means they have an important role as an uncoordinated warning system. A survey after the 1990 Maidenhead (UK) floods indicated that over 40% of the people who informally detected the flood, warned their neighbours [54]. By taking advantage of these unofficial channels people who may not hear the sirens such as deaf or elderly would be contacted with information.

10. Recommendations

None of the tsunami danger signals which were evaluated in this study met all of the requirements and recommendations for a danger signal. For example, the sting signal failed to meet the requirements because the signal is too similar to other sirens and the frequency content does not vary with time. The signals in Auckland failed to meet the requirements for several reasons, including the use of three signals which only differ in the length of the pulses to convey different meanings. The signal used in Northland was the best of the signals evaluated, but the Northland signal failed to meet the requirements because it included only a single fundamental frequency and did not include a low frequency tone. Alternatively, a danger signal which meets the requirements has been proposed.

Since the Northland signal is generated by an electronic siren, it may be possible to modify the signal to include a second tone which varies with time in the frequency range between 224 Hz to 355 Hz as shown in the waterfall plot in Figure 33.

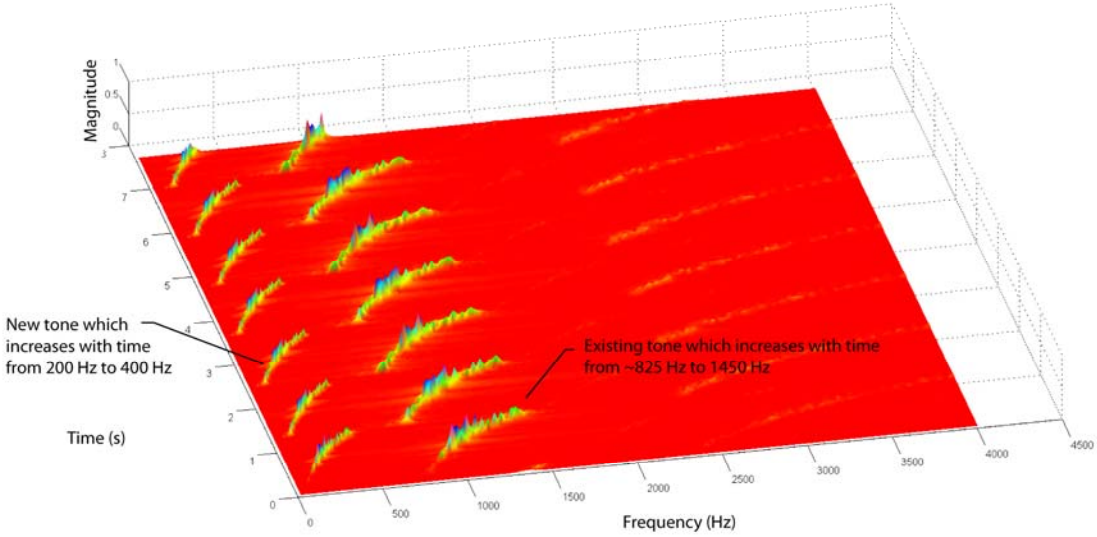

Figure 33: Simulated waterfall plot of the modified Northland signal.

The waterfall plot shows the existing tone which increases in frequency with time between approximately 825 Hz and 1450 Hz. A new, tone has been added which increases in frequency with time between 200 Hz and 400 Hz. The addition of the lower frequency component will increase the likelihood that the signal will be heard inside of dwellings and vehicles. If the lower frequency component could be added to the exiting Northland signal, the new signal would comply with the requirements and recommendations for a danger signal.

It is recommended that a signal which complies with the requirements for a danger signal should become the standard tsunami danger signal in New Zealand and should replace the currently used danger signals used with all of the electronic sirens. The use of one, standardized, fully compliant tsunami danger signal will make it easier to educate people about the signal and the appropriate responses. Furthermore, the use of one signal will reduce confusion about the meaning of the signal when people travel from one region to another. It is further recommended that areas which use more than one tsunami danger signal should reduce the number of signals used to the one standard tsunami danger signals due to the risk of confusing people as to the meaning of the different signals.

The ability to change the danger signal produced by the electronic sirens is an advantage of the electronic sirens over the mechanical sirens which can only produce one signal. The advantage of the electronic sirens is furthered by the requirement of ISO 7731 [7] that the effectiveness of the danger signal shall be reviewed at regular intervals. If changes need to be made to the danger signal produced by the sirens due to changes in the coverage area or new requirements, it is possible to do so with the electronic sirens but not the mechanical sirens.

Prior studies have shown the clear advantage of integrating a verbal warning with a non-verbal danger signal. Any verbal warning included in the danger signal should be pre-recorded and must comply with the requirements of ISO 9921 [7]. While the addition of verbal warnings is possible with electronic sirens, mechanical sirens can not be used to integrate verbal warnings.

Due to the advantages of the electronic sirens in terms of the ability to change the signals produced and the ability to integrate verbal warnings, electronic sirens are to be preferred over mechanical sirens. It is recommended that no additional mechanical sirens be installed in New Zealand for the purpose of tsunami warnings.

However, based on a suggestion by Brendan Morris, it may be possible to improve the signal generated by existing mechanical sirens used for tsunami warnings by turning off the siren after a period of T_1 seconds. Then after a period of T_2 seconds, the siren is to be turned back on. Turning on and off the siren at set periods will result in the signal shown in Figure 34.

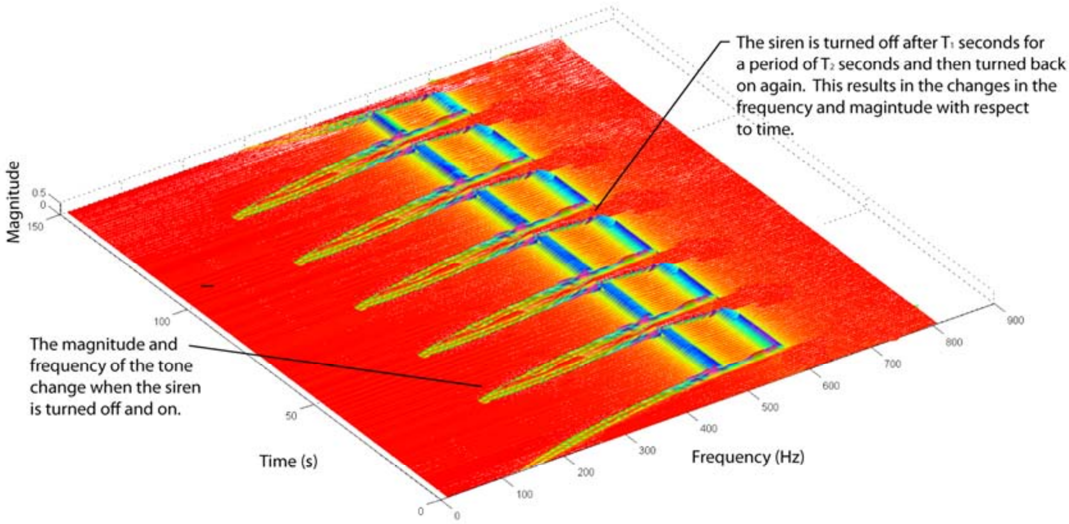

Figure 34: Simulated waterfall plot of the modified Thames Coromandel signal. The signal has been improved by turning the siren on and off, but it still is not complaint with the requirements of a danger signal.

The duration T_1 must be in excess of 5.1 seconds (the repetition rate of the fire siren) so that the signal is not mistaken for the fire siren. While the signal shown in the figure is still not complaint with the requirements of a danger signal, turning the siren on and off at set periods improves the signal by causing changes in the frequency of the tone and the signal level. These changes will improve the perception of urgency of the signal.

Regardless of the tsunami danger signal which is used, the education of the people in siren coverage area is critical for the successfully implementation of a tsunami warning system. Educating people about the sound of the signal, its meaning and the appropriate response to be taken must be an integral part of any plan to install tsunami warning signals in a community.

Appendix A: Key Terms

Ambient noise: The all-encompassing noise associated with a given environment, a composite of sounds from many sources from many directions and distances. This is often referred to as background noise, the sum of sound created by birds in one's back yard, traffic one block over, and industrial facilities miles away [10].

Atmospheric Attenuation: A still atmosphere attenuates sound as a function of the sound's frequency, temperature, relative humidity, and propagation distance. The loss is directly proportional to the distance travelled, and high frequency sounds have more atmospheric absorption loss than low frequency sounds, i.e., low frequency sounds tend to carry further [10].

Attenuation: When sound radiates away from its source, its loudness decreases with distance because its energy is spread over a progressively larger area. Additional factors that can affect the attenuation rate include the sound's frequency, prevailing weather conditions that can create atmospheric attenuation, and varied terrain/vegetation densities that can create ground absorption [10].

Audibility: The degree to which a sound can be heard by an individual. Important components of audibility include whether the sound is louder than the surrounding ambient noise and its ability attract the attention of otherwise occupied individuals [10].

Auditory Warning Signal: Signal indicating the possibility or actual occurrence of a dangerous situation requiring appropriate measures for the elimination or control of the danger. The auditory warning signal may also provide information concerning the conduct and courses of action to be taken [7].

Bursts of Sound: Normally recurrent group of sound pulses with short but distinct interruptions [9].

Directional Siren: A siren that radiates most of its sound in a beam pointing in a specific horizontal direction [48].

Effective Masked Threshold: Level of auditory danger signal just audible over the ambient noise, taking account of the acoustic parameters of both the ambient noise in the signal reception area and the listening deficiencies· (hearing protection, hearing loss and other masking effects) [7].

Effective Range: The range at which the warning signal can be heard and understood. The effective range (ER) of a warning device is dependent on three major components: the rated warning device noise level, the atmospheric conditions and the local terrain.

Electronic Siren: A siren that produces tonal sounds by amplifying the output of an electronic signal generator and broadcasting the amplified signal from one or more electrodynamic loudspeakers [48].

Estimated Time of Arrival: The time of the first tsunami wave arrival at a fixed location, estimated through modelling the speed and refraction of the tsunami waves as they travel from the source. Accuracy depends on precision of source location, earthquake magnitude and bathymetry data [57].

Evacuation Map: A drawing or representation that outlines danger zones and designates limits beyond which people must be evacuated to avoid harm from tsunami waves. Evacuation routes are sometimes designated to ensure the efficient movement of people out of the evacuation zone to evacuation shelter [58].

Frequency: The number of sound waves that pass a given point in one second. One single oscillating wave per second corresponds to 1 Hertz (Hz), the standard unit of measurement used for frequency. To the human ear, frequency is closely correlated to our perception of pitch, with fog horns and tympani drums generating low frequencies while piccolos and police whistles produce high frequency sounds [10].

Ground Absorption: A form of attenuation that occurs when the sound propagation path is close to the ground. For acoustically "soft" surfaces such as grass-covered soil, excess attenuation beyond 250 feet can be significant and, over large distances, is approximately 6 dB per distance doubled. Sound travelling through thick foliage and woods is affected to an even greater extent [10].

Hertz (Hz): A unit of frequency defined as the number of cycles per second.

Horizontally Omni-directional Siren: A siren that radiates sound approximately uniformly in all horizontal directions from the siren at the fundamental frequency of the sound [48].

Intelligibility: The degree to which a sound can be understood [10]. Intelligibility is an important consideration for audible devices using voice function.

Loudness: The human perception of a sound wave's amplitude or sheer sound pressure, and it is typically measured in decibels (dB).

Mechanical Siren: A siren that produces tonal sounds by periodically interrupting a flow of compressed air. Mechanical sirens may be motor or engine driven, and the air compressor may be integral with or separate from the flow interrupter [48].

Mechanical/Electronic Siren: A siren that uses a tone generator driven by mechanical means, and the tone generator output is applied by direct connection to loudspeakers, or through one or more electronic amplifiers to loudspeakers [48].

Natural Warnings: Naturally occurring indications that a local tsunami may occur. Strong earthquake shaking and unusual water conditions, such as rapid drawdown or sudden rise of the ocean, as well as unusual patterns of animal behaviour such as that described in the events of December 2004 in Southeast Asia are natural warnings for a tsunami from local sources. Natural warnings do not occur for distant tsunamis [48].

Octave: Bandwidth of a filter which comprises a frequency range of a factor of two [7].

Omni-Directional Siren: A siren designed to have essentially the same sound power in all directions in a horizontal plane by having multiple horns radiating out from a centre point, thereby covering the entire 360o simultaneously, i.e., without the need to rotate [10].

One-third Octave: Bandwidth narrower than an octave. The octave can be subdivided into three 1/3 octave bands. [7].

Pitch: the characteristic of a sound that makes it sound high or low or that determines its position on the musical scale. For a pure tone, the pitch is determined mainly from the frequency, although the pitch of a pure tone may also change with sound level. The pitch of complex sounds also depends on the spectrum (timbre) of the sound and its duration [59].

Recession: Drawdown of sea level prior to tsunami flooding. The shoreline moves seaward, sometimes by a kilometre or more, exposing the sea bottom, rocks, and fish. The recession of the sea is a natural warning sign that a tsunami is approaching [58].

Reflection: The phenomenon of sound "bouncing" off of hard surfaces. Reflections can be caused by vertical planes such as those created by buildings and walls, as well as acoustically "hard" horizontal surfaces such as water and desert floors [10].

Reverberation Time: Time interval required for the sound pressure level to decrease by 60 dB, after the emission by the source is stopped [7].

Rotating Siren: A directional siren that contains a mechanism to slowly rotate its beam of sound about a vertical axis [48].

Signal: The sound produced by a siren or a loudspeaker which when properly specified, will alert people to the possibility or the occurrence of a dangerous situation

Signal Reception Area: Area in which persons are intended to recognize and react to a signal [7].

Spectral Content: Overall frequency content of a signal, or of the ambient noise [7].

Sweeping Sound: Continuously or discretely varying frequency [9].

Territorial Authority: A territorial authority within the meaning of the Local Government Act 2002 [60].
Tone: Individual freqeuncy component of a danger signal. Tones that consist of a single frequency are called pure tones and tones that consist of several frequencies are called complex tones [61].

Travel Time: Time required for the first tsunami wave to propagate from its source to a given point on a coastline [58].

Tsunami: Japanese term meaning wave ("nami") in a harbour ("tsu"). A natural phenomenon consisting of a series of waves generated when a large volume of water in the sea or in a lake is rapidly displaced [1].

Two-Tone Siren: A siren designed to produce tonal sound with two simultaneous fundamental frequencies. The two fundamental frequencies are not harmonically related [48].

Unofficial Warning Systems: Processes whereby people warn those within their personal networks – whether this be within a government agency, those within other bodies or communities or those within their own communities. The unofficial warning channel is also described as a 'Contagion process' where by people hear the message and then sequentially tell others. Other names used in the literature are informal system, folk network and personal networks [54].

Warning System: a system that detects impending disaster and gives that information to people at risk and enables those in danger to make decisions and take action [42].

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