# Did You Hear That?
# Ultrasound Doppler Allows Human Echolocation by All

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**Abstract**

Individuals with visual impairments must often utilise assistive aids to enable them to complete tasks of daily living. One of these tasks, locomotion, poses considerable risk. The long white cane is often used to perform haptic exploration, but cannot detect obstacles that are not ground-based. Although several devices have been developed to provide information above waist height, they do not provide auditory streams that are easy to decipher. Development of such devices should adapt to the user, not require adaptation by the user. Can obstacle avoidance be achieved through auditory perception? This research presents an auditory interface that has been designed with the user as the primary focus. An analysis of the tasks required and the cognitive load to perform them has been taken into account resulting in an interface that audifies ultrasound. Audification provides intuitive information to the user to enable perceptive response to environmental obstacles. A device was developed that provides Doppler shift signals that are audible as a result of intentional aliasing.

## Introduction

The number of individuals with visual impairments continues to increase as the population ages. In 2001, the number of adults who had been diagnosed as blind in New Zealand was 11100 (2001 New Zealand Disability Survey Snapshot 6 – Sensory disabilities). Sensory deterioration makes it difficult for these individuals to assess their environments and generally people start to rely on aids to enhance their independence. The most commonly used aid is the long white cane. Haptic exploration is a task that is easy to learn but difficult to master. The long cane techniques taught by orientation and mobility (O&M) instructors are often modified by the user to enable quicker scanning which in turn allows them to increase their speed of walking. This results in a significant lack of path coverage endangering the individual who is unable to detect environmental changes in the path of travel (Wall & Ashmead, 2002; Uslan, 1978; Lagrow et al., 1997). Other limitations of the long cane include the inability to detect obstacles that are not rooted to the ground such as wall-mounted bookcases and overhead signs.

Several secondary mobility devices have been developed to enable auditory perception of the environment above waist height (Meijer, 1992; Kay, 2000). These include sonar and imaging devices which provide auditory pictures" to the determined, diligent user. Mapping of distance or pixel height to pitch and location to sound intensity seem logical mappings to the sighted inventor, but do not take into account the remarkable ability of the ear to filter the echoes and allow the brain to process the information. A study of individuals trained in the use of secondary mobility devices (Blasch et al., 1989) found that although 86% reported having a device in their home, only 46% had used it in the 30 days prior to the interview.

Although no dominant reason for lack of use was given, 21% suggested that design modifications would improve their usefulness. These devices have often been designed to provide as much information as possible, but the method to display this information has not been well thought through. Providing information that allows the individual to perceive their environments intuitively may increase the usefulness of such devices. Rather than engineer a device that “works”, we must systematically determine the needs of the users and address those needs.

This research seeks to discover what information should be provided in an auditory display for an individual with visual impairments and how to best provide it to the individual. The main question to be answered is: what auditory information must be displayed to a visually impaired traveller to provide sufficient information for obstacle avoidance while minimizing the cognitive load of the user?

An auditory display is one that transforms data into sound. Being able to hear differences in the environment can enable safer more efficient travel. Design of an auditory display requires an understanding of the information requirements to achieve these goals. One of the biggest problems with the current technology is the haphazard choice of auditory signals. A more carefully considered approach to design of the display must precede the design.

## Echolocation as a Means to Obtain Environmental Information

Echolocation involves the use of reflected echoes to localise obstacles in a given environment. The basis for echolocation is that sound made by an observer is reflected off surfaces in the environment. Echolocation is most often referred to in a sonar sense to discuss the responses of bats. A significant body of knowledge exists identifying the signals that bats use to communicate with each other (Lee et al., 1995) and the signal characteristics of different species of bats. The design of current sonar systems heavily rely on the bat model of echolocation. Unlike humans, the bat can independently move each ear to obtain localisation information. Another mammal that uses ultrasound echolocation to catch prey is the dolphin. Until recently, limited research has been performed on the sonar techniques of dolphins as the underwater environment poses difficulty to researchers. Dolphins, on the other hand, do not have pinnae that can be moved for directional orientation determination.

The inner ear of the dolphin is similar in function to that of the human ear though dolphins have a greater ability to interpret higher frequency signals (DeLong et al., 2007a; Au, 2004).

These mammals send out broadband signals and capitalise on the echoes to catch their prey. Studies have shown that both dolphins and humans can discriminate among objects of different size and shape based on echoed information (DeLong et al., 2007b; DeLong et al., 2007a).

Researching the nuances of dolphin echolocation may provide more valuable insight into human auditory echolocation than that of bats.

Prior to and including the first half of the twentieth century, blind individuals were taught how to locomote effectively using auditory echolocation.

There are several factors that influence the echoes off obstacles including the sound source intensity and duration, the spatial relationship of the obstacle and the presence of background noise (Kish, 1995).

If the individual is moving in a dynamic situation, Doppler shift, involving a change in frequency and thus pitch, can also be used for velocity estimation as one moves toward or away from a moving obstacle (Neuhoff J.(Ed), 2004), but this is often an intuitive response rather than a conscious determination.

With the advent of the cane and the introduction of guide dogs, echolocation is no longer taught and is believed to be "socially unacceptable" drawing too much attention to the individual.

An auditory interface that provides echoed information without causing social interference may allow individuals with visual impairments increased independence.

## Development of an auditory interface

There are two types of sound that can be used to convey information: speech and non-speech sounds. Speech refers to combinations of sound that work together to convey a specific message. Non-speech sounds are signals that are mapped to data and must be learned. Speech information has been shown to be more difficult to process than non-speech signals (Graham, 1999).

As with visual displays that use icons, there are elements of context for auditory interfacing. These include auditory icons, earcons, audification, and sonification. Earcons are abstract musical tones that are usually represented in hierarchical form to relay information. These tones must be learned by the user to be useful in interpreting the information they represent. Auditory icons represent a sound "image" of the object or motion to which it is referring. This is a direct comparison to visual icons.

A heartbeat sound can be used for monitoring pulse information (Sanderson, 2005). Audification represents direct translation of physical energy into audible sound. Seismic data have been presented very effectively using audification by increasing the frequency of ground vibrations to be within the auditory range (Dombois, 2002).

Lastly, sonification is the mapping of data streams onto auditory dimensions. The use of sonification to detect sleep apnoea has been proposed such that heart rate variability is mapped to sound signals.

These elements of context allow sound to be applied to interfaces, but how does an interface designer decide which ones would elicit the intended response?

The behavioural responses to the aforementioned elements of context can contribute to the reduction of mental workload and, in turn, stress.

Brewster has performed several studies that have shown that auditory interfacing can decrease mental workload while performing specific computer tasks (Brewster et al., 1995; Brewster & Crease, 1999; Brewster, 1997; Brewster et al., 1994). Tasks such as clicking on buttons (or icons), following menu tasks, and copying and moving files can be performed faster and with less mental workload when auditory information is used to compliment visual information.

From these studies it is noted that it is important to reduce the cognitive load of the user to minimise error.

The elements of context mentioned earlier also have behavioural responses associated with them. According to Watson and Sanderson (2007), audification and sonification are skill based behaviours such that they reflect "everyday listening" and are object focussed.

Earcons are representative of "analytic everyday listening" and are rule-based behavioural in nature. Finally, there is a realm of "knowledge-based behaviour" or learned behaviour required to interpret some earcons and sonification representing "musical listening" which is abstract and analytic.

Based on the needs of the user, different behavioural responses may be required to reduce workload and the elements of context should be chosen to reflect these needs.

The design cycle for an auditory display can help determine which elements of context suit a specific design (Watson & Sanderson, 2007). This technique allows for the development of an auditory interface which increases interpretability and

***Mobility instructors discourage echolocation, especially clicking. While training with my first dog, I forgot myself and clicked to determine if I was near a pole. The instructor told me that my dog would be taken from me if I continued to make "those sounds," that served no purpose, they made blind people objects of ridicule. And furthermore, I'd confuse the dog. I stopped clicking until I returned home! (Feinstien)***

reduces cognitive load. It consists of defining the problem, performing a needs analysis, and defining the level of cognitive control prior to the stage of design synthesis.

When this auditory display design cycle is taken into account for this problem, it is evident that audification of ultrasound is the best manner to display information to individuals with visual impairments as it closely resembles echolocation (Davies et al., 2006; Davies et al., 2007). As with seismic data, ultrasound data shares a physical phenomenon (frequency) that is readily displayed in this format (Eldridge, 2006) enabling intuitive response.

## From Echolocation to Audification

Human echolocation provides information based on direct auditory reflections. The echoes provide information about environmental layout. As an individual moves closer to an obstacle, the intensity of the echoes increases, the larger the obstacle, the more reflected echoes, creating a louder sound.

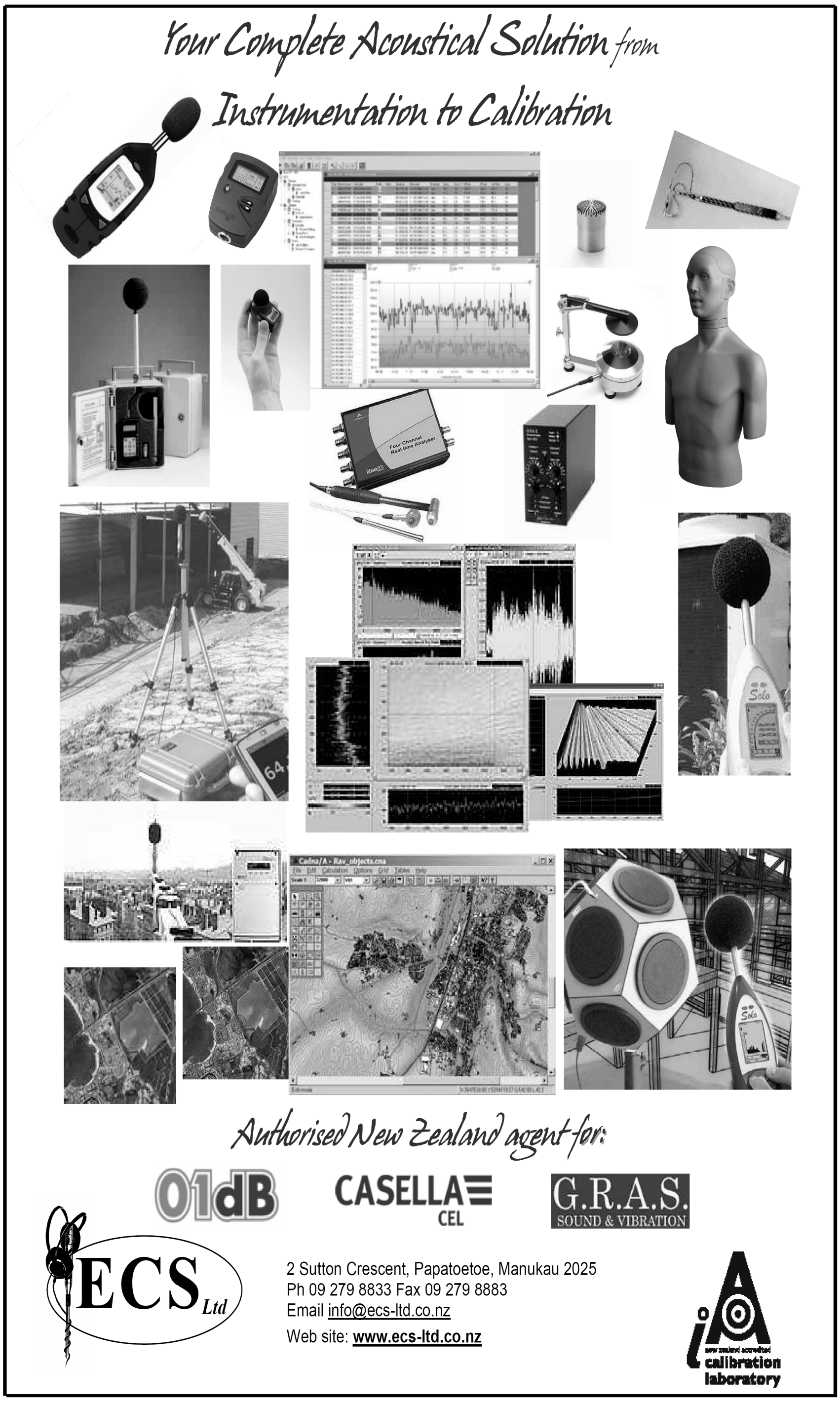
As an individual gets closer to an obstacle the reflections come back much more quickly and the subconscious is able to interpret distance information, thus the rate of approach can be deciphered and velocity can be deciphered.

An approaching pedestrian might be heard by direct sound signals or by Doppler shift. Doppler shift at the auditory frequencies is very difficult to identify as the frequency differential is so small, but may possibly be subconsciously processed.

The key to the design of a new auditory display is to attempt to provide the same characteristics to an individual with audification as would be evident through echolocation but perhaps magnifying characteristics that might enable intuitive response. Intentional aliasing of ultrasound signals to the auditory range without additional processing may provide adequate localisation characteristics. The echoed signals would provide information about all obstacles present in the given environment at a distance as far away as can be detected with the ultrasound device.

## Design of a Device to Enable Audification

An interface that purports to be intuitive and easy to use is proposed. This interface was designed with the aid of a framework identifying the key features that can enable safe and efficient response to environmental obstacles. Unfortunately, the systems that are commercially available do not allow for the application of this interface. Instead, a new system was developed that allows for audification. The discussion that ensues reports the development of a novel system that was designed in collaboration with Defiant Engineering and resembled a phased-array radar system. This device relies on Doppler to provide information about obstacles while the individual is moving (audification). A click signal can also be imposed on the signal to provide information while the individual is stationary.



## Conceptual Analysis

Since existing systems require a full interpretation of the data to be displayed to the user, rather than allowing the environmental reflection to be heard, it was necessary to develop a system that would allow for direct down-conversion of the ultrasound signals.

This system would require a transmitter (as with dolphins or humans when they are echolocating) and two receivers (ears). The signal would be sent at ultrasound to minimise the annoyance of surrounding individuals but still allow visually impaired individuals to develop a spatial map based on reflected sound or echolocation.

Phased-array radar systems provide real time data about reflections using downconversion of radar signals. This provides a good basis for the design of a human system to allow for audification.

Perhaps audification can be achieved by the direct downconversion of ultrasound signals. A hybrid system was developed taking into account human skills and an audified interface.

This system enables detection of environmental obstacles in the same manner as phased-array radar, but allows the human brain to perform many of the complex tasks (Pinder & Davies, 2007).

In the Hybrid System (Figure 1), the verbal click of human echolocation is replaced with the waveform generator of the radar system, though the waveform generated could be identical to conventional echolocation (a click, hiss, or clap).

Transmission of the waveform at an ultrasonic centre frequency provides several advantages, apart from the elimination of the social disturbance. For instance, Doppler is proportional to transmit frequency, and therefore more pronounced, allowing perception of the rate of closure with an object by a novice user.

Furthermore, the degree to which the surroundings can be illuminated is limited only by the power and dynamic range of the hardware, providing the opportunity for greater preview than is available from human echolocation.

In this case, a system with an ability to transmit sound while both stationary and moving was developed. Studies by Ashmead et al. (1995) and Rosenblum et al. (2000) found that movement toward an obstacle increased the ability to localise distances as compared to stationary echolocation. Continuous transmission of ultrasound signals in this system allows for pronounced Doppler while an individual (or another individual within the environment) is in motion.

As within the auditory range, movement toward an obstacle with the novel system complements a click with Doppler signals which should also enable more efficient localisation.

When the traveller stops moving, the clicking sound becomes more prominent. Naturally, individuals move their head to hear the source of the auditory stimulus (Munhall et al., 2004). Turning the head toward the source has shown to be most effective at localising sound sources (Middlebrooks & Green, 1991).

Dynamics of the head are intuitively incorporated in the Hybrid System in exactly the same way as long as the necessary instrumentation moves with the observer's head.

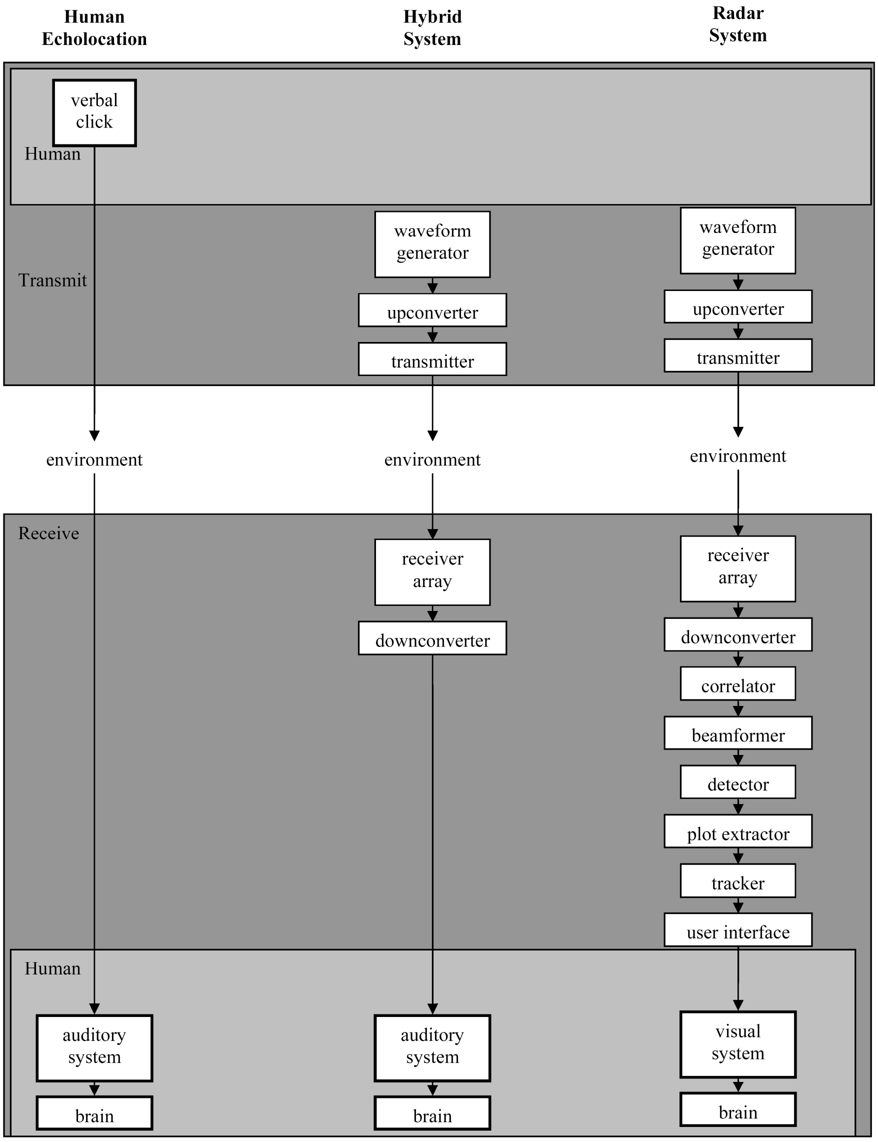



**Figure 1: The similarities among human echolocation, hybrid system echolocation, and phased array radar system (from Pinder & Davies, 2007).**

Localisation is achieved directly through head motion. This closely resembles an echolocation click that visually impaired individuals use and can allow for fine tuning the information received through ultrasound.

The theory behind intentional aliasing and Doppler shift will now be discussed ending with a description of how these are applied in the Hybrid System.

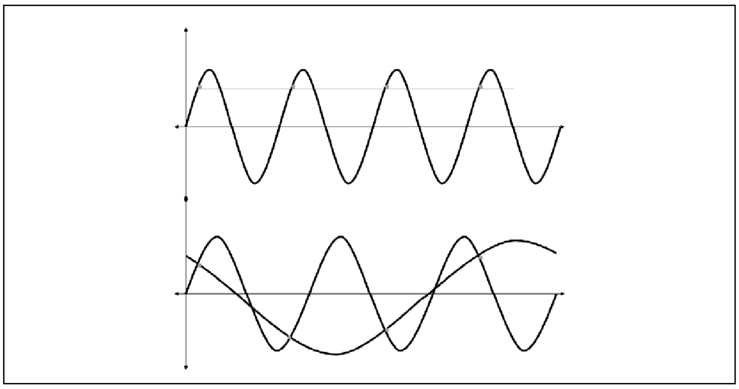


Figure 2: The top panel represents a 40 kHz signal (sine wave) which is sampled at 40 kHz (dotted). The result is a line of 0 kHz (horizontal line). The bottom panel shows a 30 kHz signal (sine wave) sampled at 40 kHz (dots) which result in the 10 kHz signal.

### Digital Downconversion

The concept of "intentional aliasing" is commonly used in radar systems to convert a signal at a high intermediate frequency to a useable digital signal. Aliasing occurs when the sample rate is lower than can be fully representative of the transmitted signal.

The Doppler Effect provides changes in the frequency of the signal and allows for perception of environmental obstacles.

Although this is not often observed in the auditory range, once a Doppler-shifted ultrasound signal is intentionally aliased (or downconverted), the user can hear environmental changes.

The next section discusses intentional aliasing and how it can allow for auditory perception of Doppler shift.

### Intentional Aliasing and Doppler Shift

The Nyquist Theorem states that the highest frequency that can be accurately represented by sampling a signal is less than one half of the sampling rate. This allows for the presence of sufficient information to draw out all components of a frequency spectrum.

Aliasing occurs when the sample rate falls below the Nyquist frequency. By sampling the ultrasound signal at a frequency lower than Nyquist, the ultrasound signal can be represented by a signal within the auditory range.

***"...As the user walks through a room with multiple obstacles, each one creates a different Doppler shift..."***

This system uses Doppler to provide information about the general environment during locomotion. If an obstacle is located in front of a person, such that the waves are reflected, a Doppler shift can be observed by the person, provided the person has sufficient sensitivity to the frequency shift. The obstacle is stationary with the transceiver walking toward it.

Thus, the received frequency,

$$f = f_0\left(1 + \frac{v_0}{v}\right)^2$$

where $f_o$ is the transmitted frequency, $v$ is the speed of wave in the medium, $v_o$ is the rate of change of distance between the transceiver and the obstacle.

Note that this differs, though only slightly, from the most basic presentation of Doppler shift in that the frequency of the waves incident on the obstacle are shifted from the transmit frequency, and the received signal is in turn shifted by the same factor again.

Let's assume that an individual is performing echolocation in the auditory range. Assume sound travels at 344 m/s in air. If a person sends out a signal at 100 Hz while traveling directly toward a stationary obstacle at an average walking speed of 1.3 m/s the perceived frequency of the return signal will be 100.76 Hz. This difference in frequency from the initial signal will be virtually undetectable to the untrained observer (0.76 Hz). It is almost impossible to detect Doppler shift by normal human movement. Kish suggests that higher frequency clicks are more easily distinguished (Kish, 1995).

If the individual clicks at 1000 Hz, the perceived frequency of the return signal will be 1007.6 Hz, thus a difference of 7.6 Hz, more perceptible, but not for the average individual.

## Audification of ultrasound

Audification is a result of intentional aliasing of Doppler shifted ultrasound echoes. In this case, the device has a transmitted signal at 40 kHz. Assume that an individual with this system is stationary. The sine wave in the top panel of Figure 1 represents one tenth of a millisecond of a 40 kHz signal. This signal is transmitted out to the environment and reflected off obstacles. When the signal returns, the signal is now sampled at 40 kHz (the green dots), a signal of 0 kHz will result (the green line) as there is no motion. Nothing can be heard. Forthe echo that is unmodified as a result of non-movement, the difference between the two signals results in a value of

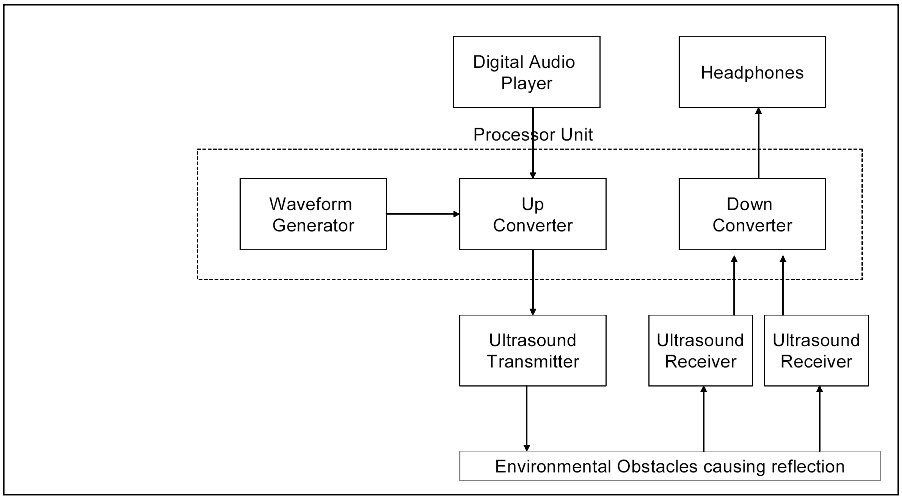



**Figure 3: Hardware components in novel system design**

zero Hertz.

Now there is movement in the environment, such that a 30 kHz signal is received (black sinusoid in lower panel of Figure 1). Sampling of this signal at 40 kHz (green dots) results in the blue sinusoid which is a 10 kHz signal, which is an alias of the original. A 10 kHz signal can be heard in the auditory range. This is an extreme example for diagrammatic purposes. Now let's visit a more realistic scenario.

The individual performing echolocation earlier was walking toward an obstacle at 1.3 m/s. If instead of generating a signal at 100 Hz or 1000 Hz, the individual can now generate a signal at 40 000 Hz, what is the result? The signal is transmitted to the environment at 40 kHz, the individual moves toward it at 1.3 m/s, the signal that is "heard" is 40 303 Hz. This signal cannot be perceived by a human whose range of hearing is limited to about 20 000 Hz.

If intentional aliasing is now applied to the signal such that it is sampled at 40 000 Hz, the resulting sound is 303 Hz. The information from the 40 kHz transmit signal has been reflected and intentionally aliased such that audification has occurred.

As the user walks through a room with multiple obstacles, each one creates a different Doppler shift depending on its location relative to the traveller, which affects the rate of closure with the moving device. One can hear the reflections off the walls based on the distance away from them and the direction of travel. The result itself is a soft "noise" with frequencies dependent on the location of the obstacles and the motion of the user.

### Hardware

The system developed is essentially a direct conversion receiver which takes the information obtained from the echoed ultrasound signal and performs intentional aliasing to within the auditory range (Figure 2). It consists of a processor which houses a waveform generator, an upconverter and a downconverter. There are two receivers which can be moved to test different directions of signal arrival as well as the transmitter. Output from the system is received by the user from the processor with headphones.

## Preliminary System Tests

The theory behind the development of this device has been suggested, but the system must be tested to ensure it operates as expected. The aliasing should not mask other environmental sounds, yet the system should provide sufficient information within the auditory range to enable localisation and distance determination. First, this theory is tested by collecting direct auditory click signals from the receivers. Next, a pilot evaluation of the intensity of the signal on approach of a wall is reported.

### *Evaluating click signals*

Although several studies have used the ability of participants to self-generate echolocating clicks to detect obstacles, a detailed description of the method used is not presented (Rice et al., 1965; Rosenblum et al., 2000). In these studies, the clicks were highly variable ranging from tongue clicks and hisses to words like "hello". Other studies have shown that for localisation, sounds must be short with a broad band of frequencies (Neuhoff J.(Ed), 2004).

Although sounds that elicit localisation responses have been

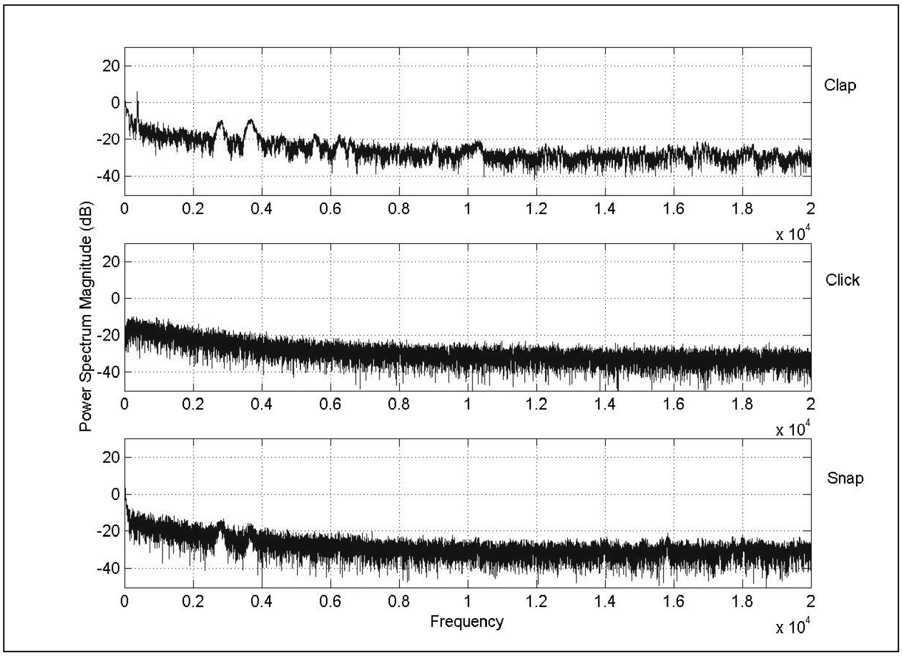



**Figure 4: PSD of common clicks: clap, click and snap**

studied, specific sounds whichprovide accurate information for echolocation have not received much attention.

There are several techniques that are known to be useful to blind individuals, though the specifics of the clicks themselves have not been studied. Kish (1995) reviews artificial and organic clicks and indicates that the benefit of artificial clicks is the ability to be repeatable both in length and spectral content.

Organic (oral or self-generated through claps or footsteps) clicks tend not to be repeatable and are often user-specific. Kish also reports that a self-generated oral click with a frequency range of 900 Hz to 8000 Hz is typical with the duration being 6.6 to 20 ms (1995).

To better understand a small sample of the sounds that are typically used in echolocation as well as to gain an understanding of the spectral signature of direct signals in an anechoic environment, sample sounds of claps, clicks, and snaps were sampled at 96 kHz. The direct signals in an anechoic environment were collected with the receivers in the aforementioned system.

The duration of these clicks was between 1.7 ms (click) and 8.2 ms (clap). Although the duration of the click is less than indicated by Kish, oral clicks are not completely repeatable.

The range of oral clicks within the five sample data collections was 1.7 ms to 4.7 ms. Figure 3 shows sample power spectral density (PSD) plots of these signals.

The clap has a strong power magnitude spike at 380 Hz, and distributed components from 2600Hz to 3000 Hz and from 3500 to 3900 Hz with an otherwise random distribution. The snap has a broad peak of higher power from 2600 Hz to 3000 Hz and another from 3600 Hz to 3800 Hz. Otherwise the signal is well distributed across all frequencies. The PSD plot of the click displays a fairly constant distribution of frequency components in the lower end of the spectrum gradually decreasing to 10 000 Hz. Based on this preliminary observation, one can see that all three signals provide broadband audible signals to the user at the lower end of the frequency spectrum. The click has the most random distribution of these broadband signals. Many blind individuals use an oral click to “illuminate” their surroundings with echoes, though even this is highly variable in the tones and pitch they self -generate.

Since this signal also comes from a source that is a constant distance from the ears, as well as being easily generated even while holding a cane, it is likely one of the best methods of localisation using echolocation for blind individuals.

It is also consistent with studies suggesting that broadband signals are more easily localised.

## Intensity Differences on Approach of a Wall

The same system was used to evaluate the intensity of the signal during a 3-metre approach to a wall that was 1.2 m wide by 2.4 m high within the anechoic chamber. The information was recorded while a person travelled toward the wall. The data shown are intensity levels with one reading per second (Figure 4). Each point represents the average intensity level over 0.5 seconds.

One would expect a gradual increase in intensity as the individual approached the door. As the individual approached the wall, there was an increase in sound pressure level of 1.21 dB over the distance of 3 m.

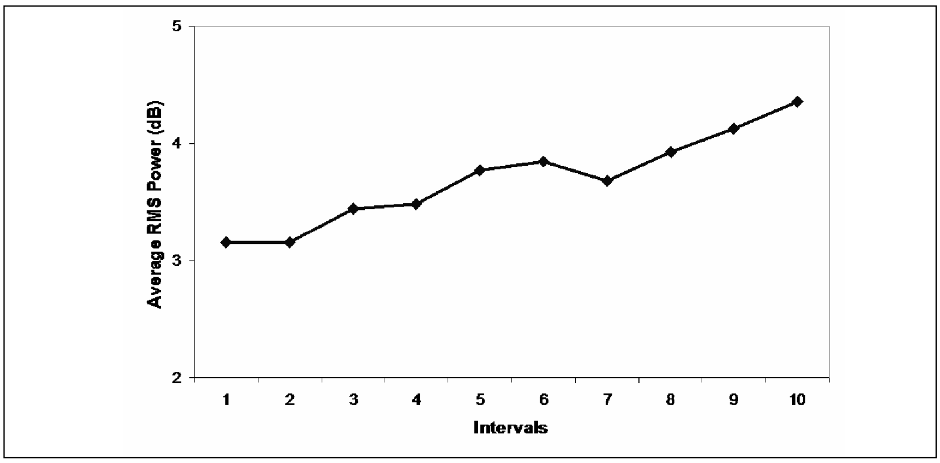



**Figure 5: The average power of the signal as the individual approached a wall.**

Although not linear, this particular graph was gathered from information of a human participant gradually walking toward a "wall" from 3 m such that it took 10 seconds.

A constant velocity device may produce more linear results, but this ultrasound system will be used for human approach and a more accurate determination of intensity relative to distance is not required.

The increase in intensity over this distance would be discernable by the human ear especially as the individual can hear the gradual increase on approach.

These two elementary tests of the system showed that the intentional aliasing of the system did not mask other sounds within the environment and the auditory intensity of the signal increased on approach to a wall.

## Summary

This work discusses the design and development of a device that provides audified ultrasoundechoes to a user directly without the need to process the signal before providing the auditory signal.

The theory behind intentional aliasing and the Doppler Effect as related to this system is presented as applied to this system. The development of the system incorporated this theory to enable audification of the ultrasound signal.

Finally some elementary testing of the device showed that it can be used as a complementary auditory system and provides similar intensity signals to those observed by true echolocation. This novel approach will allow individuals with visual impairments to better "see" the world through their own ears.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