Exploiting Ultrasound for Improved Situational Awareness

Donald W. Miklovic, Jeremy Banning, Joseph Church
Science Applications International Corporation, Acoustic and Marine Systems Operation
San Diego, Calif.
donald.w.miklovic@saic.com, jeremy.f.banning@saic.com, joseph.r.church@saic.com

ABSTRACT

Unlike humans, most mammals have the ability to hear ultrasounds, presumably for better awareness of their surroundings. A case in point is the household canine that is often aware of some unseen activity well before its owner. This paper explores the potential for ultrasound hearing technology to improve situational awareness for the individual operator.

A variety of signals of interest, such as the manipulation of firearms during pending ambush, are analyzed spectrally to determine if there is any advantage to ultrasound, and if so, how it can best be exploited. A prototype handheld device to exploit ultrasounds is presented. This device has a high-gain flat-panel ultrasound antenna; a detector to automatically determine ultrasound activity in the intended direction; and a sound conversion processor to provide the operator the option to *hear* the ultrasound activity in real-time. An example is presented where this device easily detects (with 30 dB SNR) the safety release of a handgun that is out of the line-of-sight at a range of over 100 feet in a chaotic aural environment where it is impossible to hear or detect this activity with the unaided human ear.

ABOUT THE AUTHORS

Donald Miklovic, Ph.D., is a chief scientist at SAIC with over 30 years experience in cutting-edge remote sensing R&D. He is a specialist in broadband acoustics for both underwater and in-air applications, but also has expertise in radar and optical systems. His latest initiatives include R&D for real-time high-gain microphone arrays and acoustic imaging systems for improved situational awareness in the urban environment. He holds a Ph.D. in applied mathematics from the California Institute of Technology.

Joseph Church is an electrical engineer at SAIC with four years experience in the development of advanced acoustic prototypes. He holds an M.S. in electrical engineering from San Diego State University, with focus on digital signal processing.

Jeremy Banning is an electrical engineer at SAIC with over three years experience in the development of advanced acoustic prototypes. He holds a B.S. in electrical engineering from University of California, San Diego.

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INTRODUCTION

Sound may provide information about activities that are nearby but beyond the line-of-sight. This is especially useful in military operations in urbanized terrain (MOUT), where dismounts can be blind to nearby activities occurring inside buildings, around corners, down hallways, beyond shrubs or tree lines or obscured by smoke, etc.

Unfortunately, human hearing, either with the unaided ear or through conventional microphone technology, is of limited use in the chaotic aural environments often associated with MOUT. Sounds of great interest, such as the release of a safety on an out-of-sight weapon may be noticeable at no more than a few feet - a distance too short to be tactically useful to the operator. However, if we could somehow significantly improve the individual operator's ability to hear, he would be much more aware of his surroundings in such situations.

The animal world provides evidence that this is indeed possible (see Figure 1). Most mammals, both predators and prey, have hearing that is far superior to that of humans. This is the result of two features: exceptionally large ears which collect more sound and provide highly directional hearing; and, the ability to sense ultrasound. Effectively increasing the size of the ear (e.g. cupping the hand behind the ear) is often used to improve hearing, but exploiting ultrasound is not.

Figure 1. Evidence from the animal world that better hearing would improve situational awareness.

Ultrasound is defined as any acoustic vibration at a frequency above the normal range of human hearing. This range depends on the individual, but for our purposes we will consider anything above 18 kHz to be ultrasound. We will refer to frequencies below 18 kHz as *sound*. Interestingly, as shown in Figure 2, most mammals can hear at two or three times this frequency. This begs the question "is ultrasound useful for improving situational awareness for the operator," and if so, what technology enhancements can be developed to do this? This paper looks at these issues in depth.

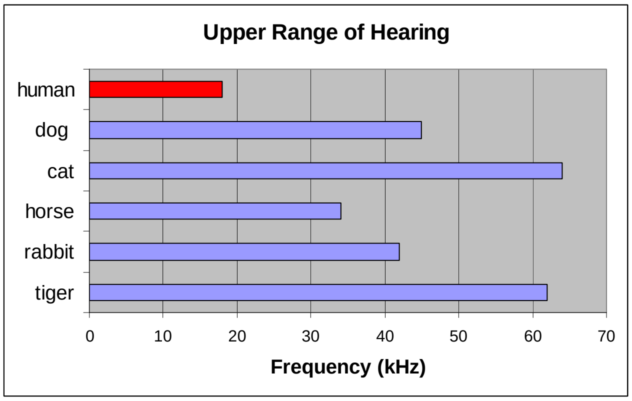

Figure 2. Most mammals can hear much higher frequencies than can humans.

THE ULTRASOUND ADVANTAGE

Ultrasound is quickly absorbed by the air and does not propagate far. Although this is a serious disadvantage for monitoring far away activities, it is a great advantage for nearby activities, since this attenuation eliminates much or all of the ambient noise that makes human hearing problematic. In human hearing, ambient noise can be quite high due to distant traffic, machinery, aircraft, gunfire, or noisy crowds, but what is *heard* with ultrasound must be coming from the immediate vicinity.

Although attenuation by air suggests that ambient ultrasound level will be very low, the signal levels of interest will also be low. To determine if there is any advantage to ultrasound, we have to look quantitatively at the relative level of signal and noise, or signal-to-noise ratio (SNR), as a function of frequency.

Attenuation and the Useful Standoff Range for Ultrasound

The signal component of the SNR will decrease exponentially with range due to absorption by the air. Figure 3 shows this attenuation as a function of frequency and humidity. At 20 kHz and 50 percent humidity, absorption is about .4 dB/meter – sound at 20 kHz would be attenuated by about 40 dB at 100 meters from its source, and higher frequencies would be attenuated even more. Therefore, any ultrasound hearing advantage would have to be for short-range situational awareness – with a practical limit somewhere around 100 meters. If shorter ranges were of interest, higher frequencies could be exploited.

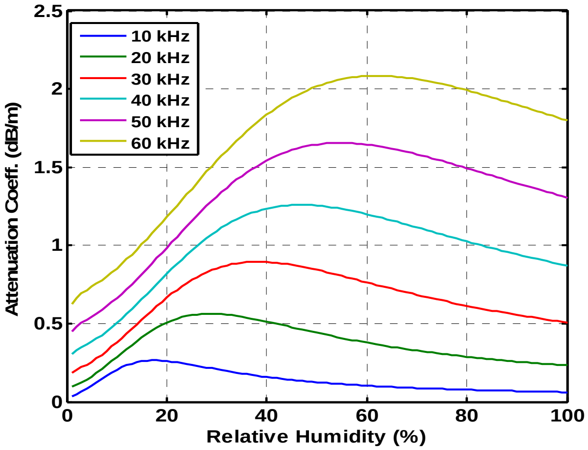

Figure 3. Attenuation coefficient as a function of percent relative humidity for several frequencies in the ultrasound range.

There are important situations in MOUT where having information about activities within 100 meters is critical. One obvious example is in building search, where a squad may approach a building on foot from a vehicle that is parked on the street no more that 20 meters from the building. It would be important to know if there is any activity inside the building prior to approach and entry. Open windows, doors or vents would be well within the range of ultrasound sensors at the parked vehicle. As the soldiers enter the building, they need good situational awareness on an even shorter scale, and hidden activities that are occurring down blind hallways, just around corners, or inside rooms would be well within the range of ultrasound.

Ambient and Self Noise Spectra

Figure 4 shows the ambient spectrum (in green) from a typical daytime suburban environment measured with an Earthworks, Inc.'s M50, an instrument-quality measurement microphone capable of high-fidelity low-noise measurements to 50 kHz (see Earthworks). The ambient level drops by 50 dB from 1 kHz to 20 kHz, giving a substantial noise advantage to ultrasound. Also shown on this plot is the spectrum of the sensor self-noise (in white). This is the sensor output with no sound entering the microphone diaphragm. The measured ambient level is about the same as the sensor noise at 15 kHz and above, so the ambient level is so low at these frequencies that the measurement is limited by sensor self-noise, and the actual ambient ultrasound level must be even lower.

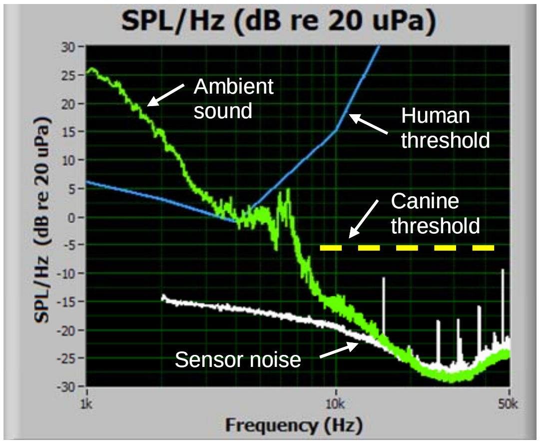

Figure 4. Sound pressure level (SPL) per 1 Hz band versus frequency to 50 kHz. Green: typical suburban ambient level; blue: threshold of human hearing; yellow: threshold of canine hearing (approximate); white: sensor electronic noise floor.

For reference, we have also shown the threshold of human and canine hearing on the same graph. The hearing threshold at a certain frequency is defined as the minimum sound pressure level (SPL) of a continuous tone which is audible. The hearing threshold, which is in units of SPL, is in different units than the ambient power spectrum (units of SPL/Hz), and so it is not immediately obvious as to how to make a direct comparison between the two. However, there is evidence that the auditory system can integrate to detect weak sounds for about one second and no longer, i.e. it can effectively filter with a 1 Hz bandwidth. With this interpretation, the hearing threshold represents the minimum SPL in a 1 Hz band that can be heard, making the power spectrum and the hearing threshold comparable in this sense.

With this interpretation, we conclude that the electronic noise for our measurement microphone is about 20 dB below the threshold of canine hearing at 20 kHz, and so, the ultrasound sensitivity of canines, and presumably other mammals, is easily surpassed with common measurement microphones.

Ultrasound Signal-to-Noise Ratio (SNR) Spectra

Spectra for various signals of interest must be compared with ambient spectra to determine if there is any signal-to-noise advantage to ultrasound. We have found it convenient to characterize the signals in terms of SNR spectra, i.e., the ratio of the signal spectrum to a typical ambient spectrum. This is because it is the SNR that determines the usability of the signal, and presenting signal levels without a direct comparison to ambient levels is not informative in terms of exploitability.

Figure 5 shows several such SNR spectra for the metallic sounds produced by weapons manipulation, where the ambient spectrum shown in Figure 4 has been used to compute the SNR. These sounds are measured at 1 meter from the source. For each case, the SNR peaks up in the 15-20 kHz range and the SNR is 40-60 dB higher at 20 kHz than at 1 kHz. The effect of attenuation has to be considered when these sounds are at greater distances, but still there would be a substantial advantage at 20 kHz for standoff ranges of 50 meters to 100 meters, where the attenuation is 20-40 dB.

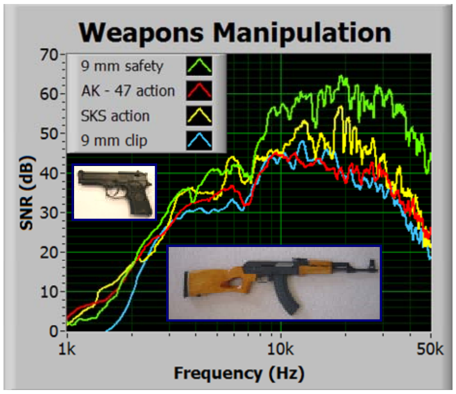

Figure 5. SNR spectra at 1 meter for metallic sounds produced by weapons manipulation.

Figure 6 shows SNR spectra for resonance sounds produced by the handling of ammunition (green) and machine screws (red), both small symmetrical metallic objects. It is noteworthy that the 9 mm parabellum round produces a distinct ultrasound resonance at about 20 kHz, which gives it a SNR advantage of more than 50 dB re 1 kHz. Not only do the ultrasound resonances provide higher SNR, but they may also be useful for determining the kind of activity being heard, i.e., weapons rounds and not machine screws.

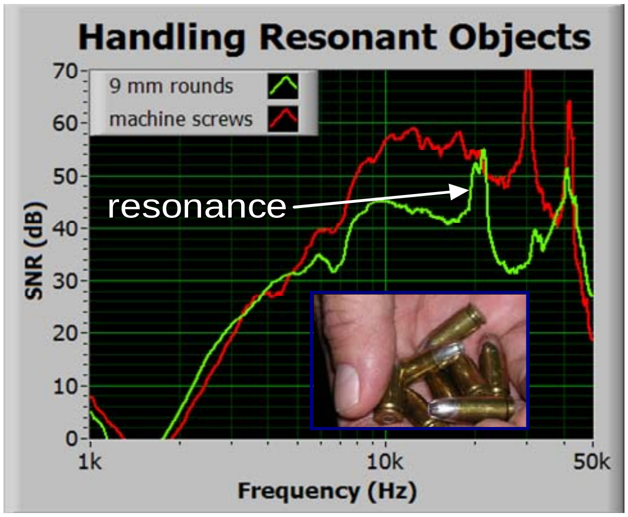

Figure 6. SNR spectra at 1 meter for resonant sounds produced by the handling of symmetrical metallic objects such as ammunition (green) or machine screws (red).

Finally, Figure 7 shows some SNR spectra for sounds that could be indicative of approaching traffic. The case where someone is approaching by foot on a trail (red) provides an ultrasound advantage of only a few dB, but the case where the approach is through brush (yellow) provides nearly a 40 dB advantage, presumably due to the rustling or snapping of twigs. The third example in the figure shows the sound produced by an approaching car (green) as the brakes are applied. Ultrasound resonances due to the brakes provide nearly a 40 dB advantage.

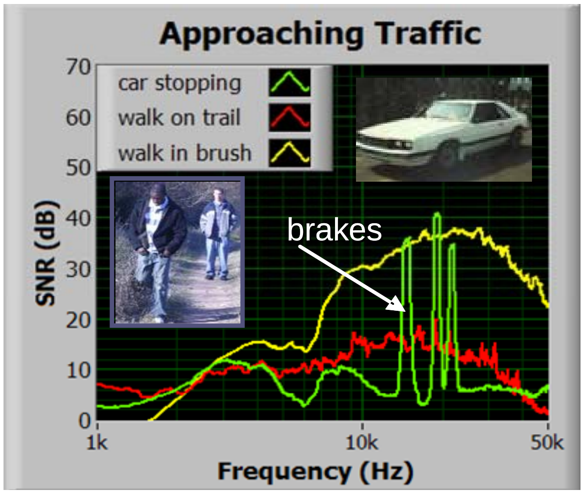

Figure 7. SNR spectra at 1 meter for sounds from approaching traffic: a stopping car (green); walking on dirt trail (red); and walking through brush (yellow)

All these examples show a SNR at 20 kHz and 1 meter distance in the range of 40-60 dB, while the SNR at 1 kHz is 0-10 dB.

Ultrasound Advantage in Chaotic Aural Environments

Ultrasound performance should not be affected by the presence of loud noises that do not have significant ultrasound components. Sources of such noise include nearby crowds; sound produced electronically by radios, TVs, public address systems, etc.; or sources of sound that are farther than 300 feet, including over-flying aircraft. To illustrate this, we have computed the SNR spectra for the sound characterized in Figure 5, but using an ambient from an environment with loud music playing instead of the typical ambient environment from Figure 4. These results are shown in Figure 8 (note the scale change in SNR from that of Figure 5). We see that the SNR has not changed at the ultrasound frequencies, but has decreased to almost -30 dB near 1 kHz. Thus, the loud music has no impact on the ability to monitor the ultrasounds, and the advantage of ultrasound over audio has increased to about 80 dB!

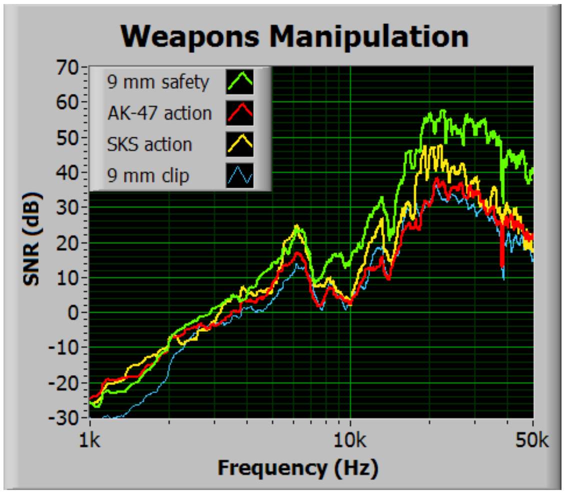

Figure 8. SNR spectra for the same sounds as Figure 5, but with loud music as the ambient noise. The SNR advantage at 20 kHz is now as high as 80 dB re 1 kHz.

Ultrasound Advantage with Microphone Arrays

As previously noted, the measurement microphones used to determine ambient levels were self-noise limited. Therefore, the ultrasound advantages quantified in the previous sections can be further increased if the sensor self-noise is reduced.

One way to reduce self-noise is with an array of microphones. Since self-noise should be uncorrelated sensor-to-sensor, noise would be reduced (in dB) by 10 log (N), regardless of the sensor spacing, where N is the total number of sensors employed. Since there is no minimum spacing requirement, small arrays of a large number of sensors are possible. For example, an array of 100 sensors could be put into a 5 cm x 5 cm surface, and if they were all combined to add the signal of interest coherently (i.e., in phase), the SNR would be increased by 20 dB over the single microphone result for situations where performance is self-noise limited.

Once electronic noise is sufficiently reduced, ambient ultrasound noise, which was too low to be detected on a single microphone, may become the limiting factor. An array of sensors can also substantially improve performance against ultrasound noise, but the sensors must be spaced at least one-half the acoustic wavelength to be effective, and so, the required physical array size (linear dimension) scales directly with acoustic wavelength for a given array performance. Since ultrasound has a relatively short wavelength, this allows high-performance arrays to be built in a very small footprint – something that can be handheld and conveniently carried by the dismount. For example, the wavelength λ at 20 kHz is 1.7 cm, and a 10 x 10 array of microphones spaced at λ/2 could be fit on a 10 cm square – something that is easily hand-held. By contrast, the corresponding 10 x 10 array designed for 2 kHz operation would be about 1 meter square – something that is not readily portable.

Array microphones can be easily summed in analog to form a single high-performance beam that is pointed manually by the operator, or the data can be digitized and one or more beams steered electronically (see Miklovic, et. al., 2009)

LOW-COST ULTRASOUND ARRAYS

Commercial off-the shelf (COTS) low-noise ultrasound measurement microphones are expensive. An instrument we often use in the lab for ultrasound measurements, an Earthworks *M50* microphone with a Zero *Distortion* preamp, is shown in Figure 9. This configuration provides calibrated ultrasound measurements to 50 kHz, at a price of about $2,000 per channel. If one is to build an array of 100 or more microphones, something less expensive is needed.

Figure 9. COTS hardware for quality low-noise measurement of ultrasound. Left: Earthworks M50 condenser microphone; Right: Earthworks, Inc.'s Zero Distortion preamp.

Electret condenser microphones such as the Panasonic® WM-64 (Panasonic Corporation of North America) shown in Figure 10 provide a good low-cost alternative for sound arrays (Miklovic, et al., 2009), but might not be expected to work well for ultrasound. The manufacturer's specifications for these microphones claim a frequency response of 20 Hz- 16 kHz (Panasonic). In fact, these microphones often do not perform well above 15 kHz in typical mounting configurations.

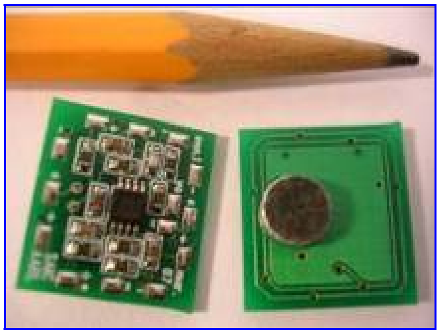

Figure 10. A low-cost electret condenser microphone which provides a good low-cost alternative for audio arrays.

However, we have found that if these microphones are properly and precisely surface mounted, they provide excellent low-noise ultrasound sensing up to at least 30 kHz. The WM-64 microphone element, without supporting preamp electronics, has a unit cost less than $2 and can operate on as little as 2 VDC, which makes it a good candidate for low-cost ultrasound arrays of a large number of microphones.

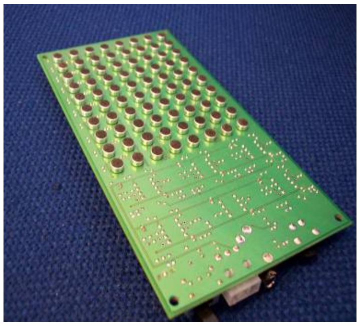

Figure 11. An 80-element flat panel ultrasound array with associated custom electronics. The faceplate, which is critical for use above 10 kHz, is not shown.

Using WM-64 microphones, we have developed a handheld flat-panel 80-element ultrasound array shown in Figure 11. The microphones are mounted directly to a custom PCB that has low-noise preamps, filters, and an analog summing circuit that provides a single ultrasound listening beam pointing normal to the array (cf. Horowitz and Hill, 1989). A faceplate, which is critical for use above 10 kHz, is not shown. The array is powered by two 9-volt batteries mounted to the back of the array.

The self-noise of this array, along with that of the M50 shown previously, is shown in Figure 12. We see that the array is substantially better than the measurement microphone for high frequency sound and ultrasound detection, being about 15 dB quieter over the entire band from 10-50 kHz.

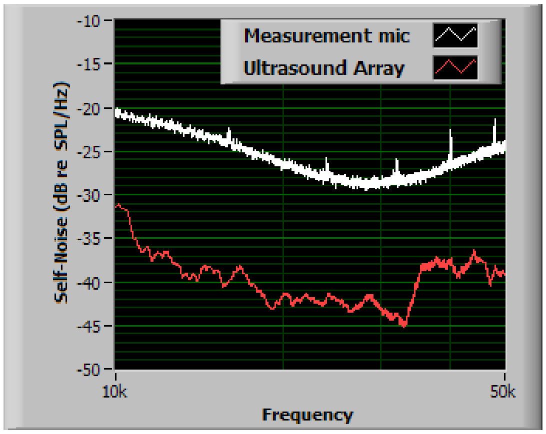

Figure 12. Self-noise for a quality low-noise measurement microphone (white) and the ultrasound array (red).

This microphone array is very directional, which provides the additional benefit of being able to focus on sounds coming from the intended direction. The best measure of this characteristic is the beam pattern (cf. Van Trees, 2002). The beam pattern is the array response to sounds as a function of direction relative to the array pointing direction. Figure 13 shows the measured broadband beam pattern over 20-30 kHz as a function of azimuth for sounds arriving at zero elevation (with the array oriented so that the long dimension is horizontal and the short dimension is vertical). We see that the 3 dB beam width in the horizontal is about 10 degrees, and that the side lobe levels past 30 degrees are at least -15 dB. This means that any ultrasounds occurring to the side of the pointing directing will be significantly reduced.

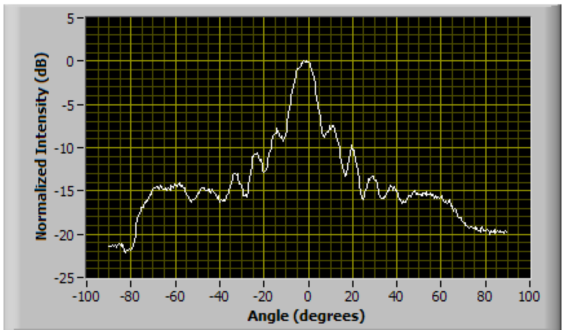

Figure 13. Broadband beam pattern over 20-30 kHz for the array of Figure 11.

THE ULTRASOUND RADIO

Real-time Prototype

A fully functional software-defined *ultrasound radio* with a high-gain ultrasound *antenna* has been developed in a small handheld package as shown in Figure 14. The 80-microphone array described above serves as the antenna. The data from the antenna is digitized at 12 bits and 200 ksps using an analog-to-digital converter (ADC) mounted on the antenna frame. This data is transferred to a micro-PC via USB cable. The micro-PC runs the ultrasound radio software, which converts ultrasound signals to the audible range and also provides automated detection and alert signals. The user interface, including real-time spectrum scope and tuning controls, is displayed on a high-resolution touch-sensitive screen, giving the user convenient control of all the ultrasound radio features. The user has the option of listening to the converted ultrasounds or of relying on automated detection processing to identify alerts.

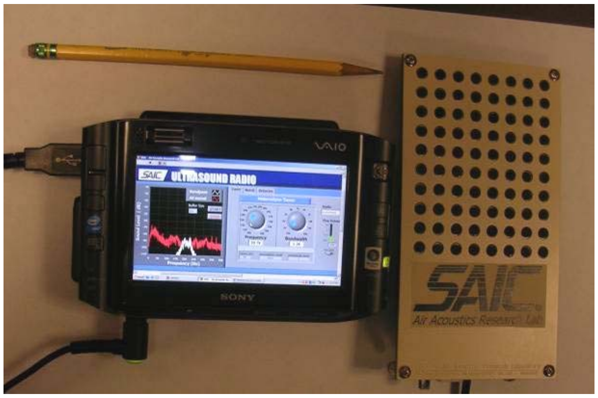

Figure 14 A software-defined ultrasound radio integrated with a high-gain array, using a micro PC for processing and touch control interface.

Hearing Ultrasounds

In order to hear ultrasounds, we have developed real-time software that converts ultrasounds to the audible range, much like a communications receiver converts radio frequency (RF) signals to audio. The control panel for this radio is shown in Figure 15. It has all the features of an advanced communications receiver, such as band tuning, spectrum scope, adjustable bandwidth, band-nulling filters, adjustable filter skirts, various demodulation modes, automatic gain control (AGC), digital recording, etc.

By monitoring the sounds, the operator can often determine the nature of the sound, providing a natural filtering for activities that may be of interest. We cannot provide examples of this in the report, but these are provided in the presentation.

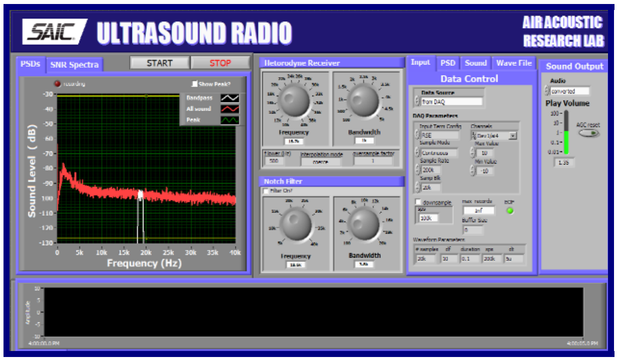

Figure 15. Ultrasound radio touch-sensitive user interface with all the features of a modern communications receiver.

Ambush Awareness Example

As a test and demonstration of these general concepts, as well as the ultrasound radio's capability, we operated the radio it in a realistic building-search scenario where there was unseen personnel preparing for ambush. To provide a controlled test activity, we released the safety on a 9 mm handgun. The handgun was located about 80 feet down a long hallway and around a corner out of line-of-sight of the ultrasound radio operator, as indicated in Figure 16. The view as seen by the operator during the handgun release is shown in Figure 17. Clearly there is nothing untoward that can be seen from this position.

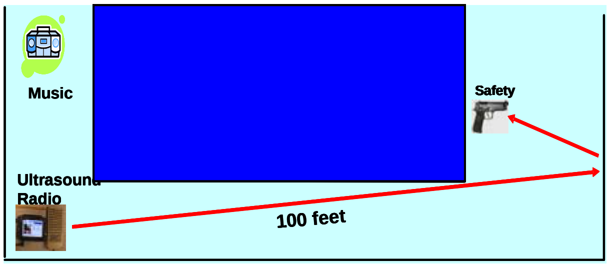

Figure 16. Geometry for testing effectiveness of the ultrasound radio in a building search scenario. Ultrasound reflects around the corner (red) to arrive at the radio after about 100 feet of propagation.

Figure 17. View from the location of the ultrasound radio toward the person with the handgun.

The total propagation distance between the source of sound and the receiver, assuming reflection from a nearby wall, was about 100 feet. For an interfering source of noise, we added a modest level of background music at 65 dB re SPL (C-weighted) near the operator as indicated in Figure 16. A 50 kHz measurement microphone (Earthworks M50) was used to collect data at the same location as the ultrasound radio antenna.

When the handgun safety is released, the sound is clearly audible with radio, but the loud music t playing nearby is not. Furthermore, the sound presented to the operator is similar to the sound of a safety release to the unaided ear, allowing the operator to distinguish it from other metallic sounds such keys jingling. Wave files of the natural audio and the ultrasound converted to audio during the safety release are provided in the presentation of this paper.

Since we cannot provide this audio result in this paper, we instead show some plots from the data to show how detectable this sound actually is. In Figure 18, plots of an automated detector output versus time are shown during the handgun safety release. Detectors are shown for a typical audio band of 500 Hz – 5500 Hz band using the M50 measurement microphone, the 20-22 kHz band using the M50, and the 20-22 kHz band using the ultrasound radio. The reference microphone was sampled at 200 ksps with a single-pole anti-alias filter 50 kHz, and had a noise floor of -28 dB SPL/Hz at 25 kHz.

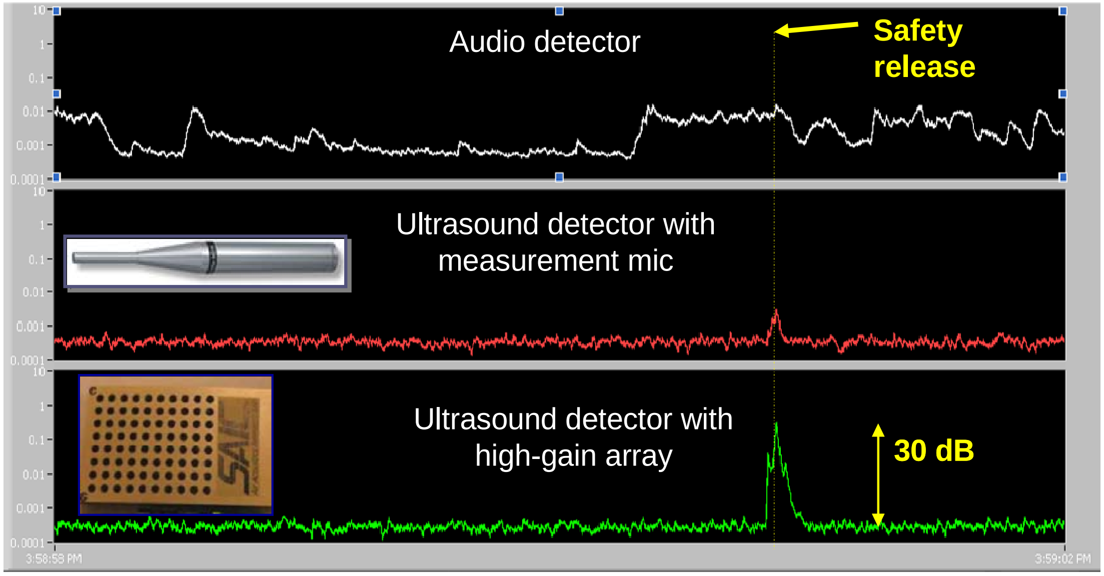

Figure 18. Non-line-of sight detection of a handgun safety release at 100 feet. Top (white), the 500-5500 Hz audio band using a 50 kHz reference microphone; middle (red), the 20-22 kHz band using the same reference microphone; bottom (green), the ultrasound radio with high-gain antenna tuned to 20-22 kHz.

The measurement microphone could detect the safety release with a SNR of about 10 dB in the ultrasound band, while the ultrasound radio detected with an SNR of 30 dB. In the audio band, there is not the slightest indication of the signal being present. The ultrasound radio provided more than a 20 dB improvement over the measurement microphone, which itself could readily detect the safety release using ultrasound frequencies. We expect that we could detect the safety release to a at least 200 feet with the current prototype, and even further with a higher-gain array, or louder signals.

SUMMARY AND CONCLUSIONS

In the immediate vicinity an individual operator there are sounds of interest that are impossible to detect or hear using the unaided ear or conventional audio technology, but can be readily detected and *heard* using ultrasound. Such sounds include the manipulation of weapons, which would indicate a potential pending ambush. Furthermore, low-cost high-performance handheld arrays that substantially improve detection range and precisely determine the direction of sound are feasible.

For the prototype ultrasound radio system presented in this paper, we have been able to achieve an impressively low noise floor of -43 dB re SPL/Hz over 20-30 kHz, which is about 15 dB better than the best ultrasound-capable measurement microphone. This system should be able to detect the safety release of a 9 mm handgun to about 200 feet in non-line-of-sight situations in very noisy environments, and further distances are expected with improvements to the array.

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