Defense Applications of Acoustic Signal Processing

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Acoustic signal processing for enhanced situational awareness during military operations on land and under the sea.

Introduction and Context

Warfighters use a variety of sensing technologies for reconnaissance, intelligence, and surveillance of the battle space. The sensor outputs are processed to extract tactical information on sources of military interest. The processing reveals the presence of sources (*detection process*) in the area of operations, their identities (*classification* or *recognition*), locations (*localization*), and their movement histories through the battle space (*tracking*). This information is used to compile the common operating picture for input to the intelligence and command decision processes. Survival during conflict favors the side with the knowledge edge and superior technological capability. This article reflects on some contributions to the research and development of acoustic signal-processing methods that benefit warfighters of the submarine force, the land force, and the sea mine countermeasures force. Examples are provided of the application of the principles and practice of acoustic system science and engineering to provide the warfighter with enhanced situational awareness.

Acoustic systems are either *passive*, in that they exploit the acoustic noise radiated by a source (its so-called *sound signature*), or active, where they insonify the target and process the echo information.

Submarine Sonar

Optimal Beamforming

The digitization (i.e., creating digital versions of the analog outputs of sensors so that they can be used by a digital computing system) of Australia's submarines occurred 35 years ago with the Royal Australian Navy Research Laboratory undertaking the research, development, and at-sea demonstration of advanced next-generation passive sonar signal-processing methods and systems to improve the reach of the sensors and to enhance the situational awareness of a submarine.

A passive sonar on a submarine consists of an array of hydrophones (either hull mounted or towed) that samples the underwater acoustic pressure field in both space and time. The outputs of the spatially distributed sensors are combined by a beamformer, so that signals from a chosen direction are coherently added while the effects of noise and interference from other directions are reduced by destructive interference. The beamformer appropriately weights the sensor outputs before summation so as to enhance the detection and estimation performance of the passive sonar system by improving the output signal-to-noise ratio. This improvement in the signal-to-noise ratio relative to that of a single sensor is referred to as the *array gain* (see Wage, 2018; Zurk, 2018).

After transformation from the time domain to the frequency domain, the hydrophone outputs are beamformed in the spatial frequency domain to produce a frequency-wave number power spectrum. (The wave number is the number of wavelengths per unit distance in the direction of propagation.) A conventional delay-and-sum beamformer, where the weights are set to unity, is optimal in the sense that the output signal-to-noise ratio is a maximum for an *incoherent* noise field. However, when the noise field includes *coherent* sources (such as interference), then an adaptive beamformer that is able to maximize the output signal-to-noise ratio by applying a set of weights that are *complex numbers* is implemented. This has the effect of steering a null in the direction of any unwanted interference (a jammer).

Figure 1 shows a comparison of the frequency-wave number spectrum for an actual underwater acoustic field sensed by an array using the conventional weight vector ***(left)*** and an adaptive weight vector ***(right)*.** The adaptive beamformer suppresses the side lobes and resolves the various contributions to the acoustic pressure field, which are shown as surfaces (ridges) associated with towed array self-noise (structural waves that propagate along the array in both axial directions, i.e., aft and forward); tow-vessel radiated noise observed at, and near, the forward end-fire direction (i.e., the direction of the longitudinal axis of the array) for the respective direct propagation path and the indirect (surface-reflected) multipath; and three surface ship contacts. The adaptive beamformer better delineates the various signal and noise sources that compose this underwater sound field (Ferguson, 1998).

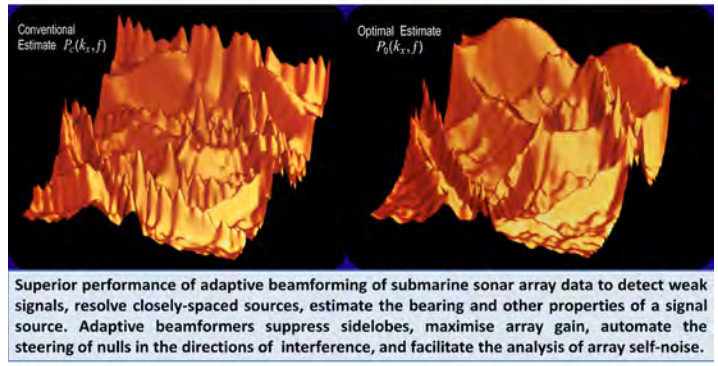

Figure 1. Left: *estimated frequency-wave number power spectrum for a line array of hydrophones using the conventional frequency-domain beamforming method. The maximum frequency corresponds to twice the design frequency of the array.* ***Right:*** *similar to the left hand side but for an adaptive beamformer. From Ferguson (1998).*

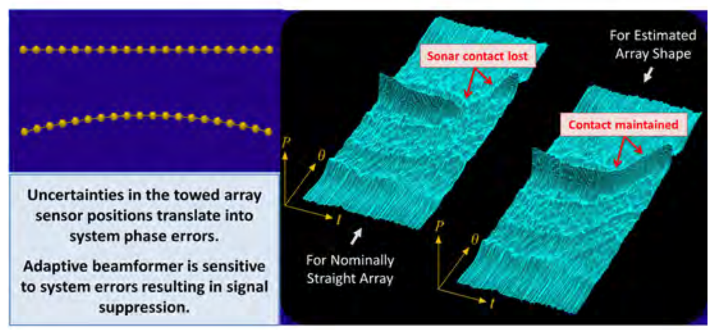

Figure 2. Left: *a towed array is straight before the submarine maneuver, but it is bowed during the maneuver.* ***Right:*** *variation with bearing and time of the output of the beamformer before, during, and after the change of heading of the submarine. The total observation period is 20 minutes, and the data are real. When the array is straight, the contact appears on one bearing before the maneuver and on another bearing after the maneuver when the submarine is on its new heading and the array becomes straight again. Estimating the array shape (or the coordinates of the sensor positions in two dimensions) during the heading changes enables contact to be maintained throughout the submarine maneuver. From Ferguson (1993a).*

Towed-Array Shape Estimation

When deep, submarines rely exclusively on their passive sonar systems to sense the underwater sound field for radiated noise from ships underway and antisubmarine active sonar transmissions. The long-range *search sonar* on a submarine consists of a thin flexible neutrally buoyant streamer fitted with a line array of hydrophones, which is towed behind the submarine. Towed arrays overcome two problems that limit the performance of hull-mounted arrays: the noise of the submarine picked up by the sensors mounted on the hull and the size of the acoustic aperture being constrained by the limited length of the submarine.

Unfortunately, submarines cannot travel in a straight line forever to keep the towed array straight, so the submarine is "deaf" when it undertakes a maneuver to solve the left-right ambiguity problem or to estimate the range of a contact by triangulation. Once the array is no longer straight but bowed, sonar contact is lost (**Figure 2**).

Rather than instrumenting the length of the array with heading sensors (compasses) to solve this problem, the idea was to reprocess the hydrophone data so that the shape of the array could be estimated at each instant during a submarine maneuver when the submarine changes course so that it can head in another direction (Ferguson, 1990). The estimated shape had to be right because a nonconventional (or adaptive) beamformer was used to process the at-sea data. Uncertain knowledge of the sensor positions results in the signal being suppressed and the contact being lost. The outcome is that submariners maintain their situational awareness at all times, even during turns.

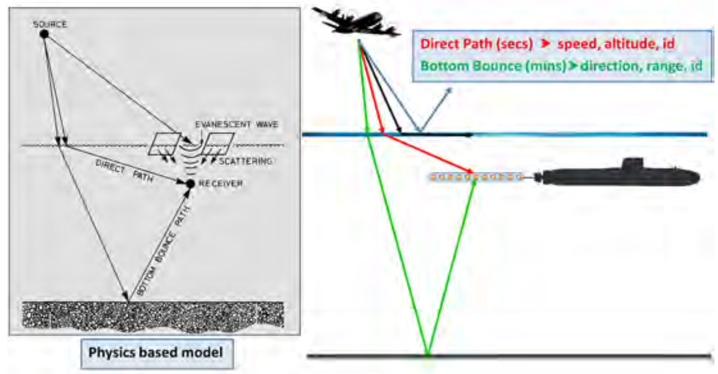

*Figure 3. **Left:** contributions made by an acoustic source in the air to the sound field at a receiver in the sea. From Urick (1972). **Right:** ray paths for a bottom bounce (**green arrows**), direct refraction (**red arrows**), critical angle where the refracted ray lies along the sea surface (**black arrows**), and sea surface reflection (**blue arrows**). See text for further explanation.*

Compiling the Air Picture While at Depth

During World War II, aircraft equipped with centimeter-wavelength radars accounted for the bulk of Allied defeats of U-boats from 1943 to 1945. U-boats spent most of their time surfaced, running on diesel engines and diving only when attacked or for rare daytime torpedo attacks (Lansford and Tucker, 2012).

In 1987, a series of at-sea experiments using Australian submarines and maritime patrol aircraft demonstrated the detection, classification, localization, and tracking of aircraft using a towed array deployed from a submarine (Ferguson and Speechley, 1989). The results subsequently informed the full-scale engineering development of the Automated Threat Overflight Monitoring System (ATOMS) for the US Navy submarine force. ATOMS offers early warning/long-range detection of threat aircraft by submerged submarines via towed arrays (Friedman, 2006).

In a seminal paper, Urick (1972) indicated the possible existence of up to four separate contributions to the underwater sound field created by the presence of an airborne acoustic source. **Figure 3, *left,*** depicts each of these contributions: direct refraction, one or more bottom reflections, the evanescent wave, and sound scattered from a rough sea surface. When the aircraft flies overhead, its radiated acoustic noise travels via the direct refraction path where it is received by a hydrophone (after transmission across the air-sea interface). Now, the ratio of the speed of sound in air to that in water is 0.22; at a critical angle of incidence ($\emptyset_c$) = 13°, the ***black arrows*** in **Figure 3** (the incident ray in air and the refracted ray along the sea surface) depict the propagation path of a critical ray. The transmission of aircraft noise across the air-sea interface occurs when the angle of incidence is less than $\emptyset_c$ (**Figure 3**, ***red arrows***). For angles of incidence greater than $\emptyset_c$, the radiated noise of the aircraft is reflected from the sea surface, with no energy being transmitted across the air-sea interface (**Figure 3**, ***blue arrows***).

The reception of noise from an aircraft via the direct path relies on the aircraft being overhead. This transitory phenomenon lasts for a couple of seconds; its intensity and duration depend on the altitude of the aircraft and the depth of the receiver. Submariners refer to the overhead transit as an aircraft "on top." Urick (1972) estimated the altitude of the aircraft by measuring the intensity and duration of the acoustic footprint of the aircraft. An alternative approach is to measure the variation in time of the instantaneous frequency corresponding to the propeller blade rate of the aircraft and then extract tactical information on the speed (using the Doppler effect), altitude (using the rate of change of the instantaneous frequency), and identification (from the source/rest frequency of the blade rate) of the aircraft (Ferguson, 1996). For a submariner, the upside of an aircraft on top is identification of the aircraft and its mission profile by processing the output of a single hydrophone without giving away the position of the submarine; the downside is that there is no early warning.

The long-range detection of a submarine relies on reception of the radiated noise from the aircraft after undergoing one (or more) reflections from the seafloor (Ferguson and Speechley, 2009). The intensity of the noise from the aircraft received via direct refraction is considerably stronger (by 20 to 30 dB) than for propagation involving a seafloor reflection, so a towed array is required to detect the Doppler-shifted propeller blade rate (and its harmonics) and to measure its angle of arrival (bearing). A submarine with its towed array deployed has many minutes warning of an approaching aircraft. In **Figure 3, *right*,** the ***green arrows*** depict a bottom bounce path that enables the long-range detection of an aircraft.

Estimating the Instantaneous Range of a Contact

The towed-array sonar from a submarine is only able to measure the bearing of a contact. To estimate its range, the submarine must undertake a maneuver to get another fix on the contact and then triangulate its position. This process takes tens of minutes. Another approach is to use wide-aperture array sonar, which exploits the principle of passive ranging by wave front curvature to estimate the bearing and range of the contact at any instant, without having to perform a submarine maneuver (see **Figure 4**, ***left***). The radius of curvature of the wave front equates to the range. Measurement of the differences in the arrival times (or time delays τ_{12} and τ_{23}) of the wave front at two

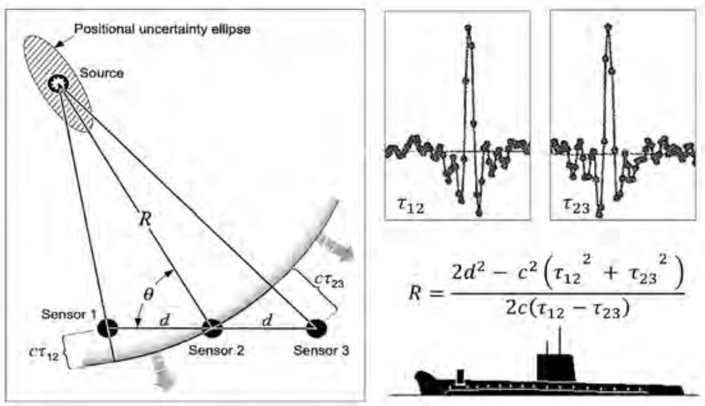

Figure 4. Left: *schematic showing the source-sensor configuration for passive ranging by a wave front curvature.* ***Right:*** *cross-correlation functions for the outputs of sensors 1,2 and sensors 2,3. The time lags corresponding to the peaks in the two cross-correlograms provide estimates of the time delays* $\tau_{1,2}$ *and* $\tau_{2,3}$ *. These time delays are substituted into the passive ranging equation to calculate the range (*R*).* c*, Speed of sound traveling in the underwater medium;* d*, intersensor separation distance. From Ferguson and Cleary (2001).*

adjacent pairs of sensors enables estimation of the source range from the middle array and the source bearing with respect to the longitudinal axis of the wide-aperture array. Measuring a time delay involves cross-correlating the receiver outputs. The time delay corresponds to the time lag at which the cross-correlation function attains its maximum value.

Figure 4, *right*, shows the cross-correlation functions for sensor pairs 1,2 and 2,3. In practice, arrays of sensors (rather than the single sensors shown here) are used to provide array gain. It is the beamformed outputs that are cross-correlated to improve the estimates of the time delays. Each array samples the underwater sound field for 20 s, then the complex weights are calculated so that an adaptive beamformer maximizes the array gain, suppresses side lobes, and automatically steers nulls in the directions of interference. The process is repeated every 20 s because the relative contributions of the signal, noise, and interference components to the underwater sound field can vary over a period of minutes. In summary, beamforming and prefiltering suppress extraneous peaks, which serve to highlight the peak associated with a contact (Ferguson, 1993b).

Battlefield Acoustics

Extracting Tactical Information with a Microphone

In 1995, sonar system research support to the Royal Australian Navy Oberon Submarine Squadron was concluded, which ushered in a new research and development program for the Australian Army on the use of acoustics on the battlefield. Battlefield acoustics had gone out of fashion and became dormant after the invention of radar in the 1930s. The Australian Army's idea was that the signal-processing techniques developed for the hydrophones of a submarine be used for microphones deployed on the battlefield. The goal was "low-cost intelligent acoustic-sensing nodes operating on shoestring power budgets for years at a time in potentially hostile environments without hope of human intervention" (Hill et al., 2004).

The sensing of sound on the battlefield makes sense because acoustic sensors are passive;

- sound propagation is not limited by line of sight;
- the false-alarm rate is negligible due to smart signal processing;
- unattended operation with only minimal tactical information (what, when, where) being communicated to a central monitoring facility;
- sensors are light weight, low cost, compact, and robust;
- acoustic systems can cue other systems such as a cameras, radars, and weapons;
- acoustic signatures of air and ground vehicles enable rapid classification of type of air or ground vehicle as well as weapon fire; and
- military activities are inherently noisy.

The submarine approach to wide-area surveillance requires arrays with large numbers of closely spaced sensors (submarines bristle with sensors) and the central processing of the acoustic sound field information on board the submarine. In contrast, wide-area surveillance of the battlefield is achieved by dispersing acoustic sensor nodes throughout the surveillance area, then networking them and using decentralized data fusion to compile the situational awareness picture. On the battlefield, only a minimal number of sensors (often, just one) is required for an acoustic-sensing node to extract the tactical information (position, speed, range at the closest point of approach to the sensor) of a contact and to classify it. For example, in 2014, the Acoustical Society of America (ASA) Technical Committee on Signal Processing in Acoustics posed an international student challenge problem (available at bit.ly/1rjN3AG) where the students were given a 30-s sound file of a truck traveling past a microphone (Ferguson and Culver, 2014). By processing the sound file, the students were required to extract the tactical information so that they could respond to the following questions.

- What is the speedometer reading?
- What is the tachometer reading?
- How many cylinders does the engine have?

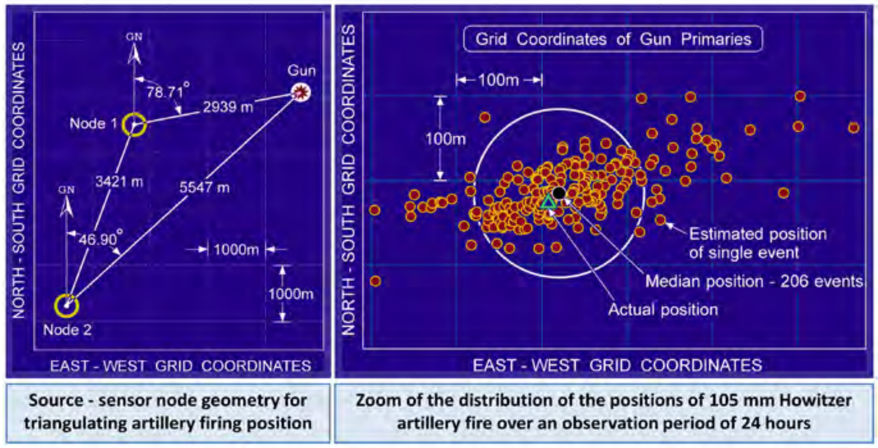

***Figure 5. Left:** source-sensor node geometry. **Right:** zoom acoustic locations of artillery fire. From Ferguson et al. (2002).*

- When is the vehicle at the closest point of approach to the microphone?
- What is the range to the vehicle at the closest point of approach?

The solution to this particular problem, together with the general application of acoustic signal-processing techniques to extract tactical information using one, two, or three microphones can be found elsewhere (Ferguson, 2016). The speed of the truck is 20 km/h and the tachometer reading is 2,350 rpm. It has 6 cylinders and its closest point of approach to the microphone is 35 m.

Locating the Point of Origin of Artillery and Mortar Fire

Historically, sound ranging, or the passive acoustic localization of artillery fire, had its genesis in World War I (1914-1918). It was the procedure for locating the point where an artillery piece was fired by using calculations based on the relative time of arrival of the sound impulse at several accurately positioned microphones. Gun ranging fell into disuse, and it was replaced by radar that detected the projectile once it was fired. However, radars are active systems (which make them vulnerable to counter attack) and so the Army revisited sound ranging with a view to complement weapon-locating radar.

Figure 5, ***left***, shows two acoustic nodes locating the point of origin of 206 rounds of 105 mm Howitzer fire by triangulation using angle-of-arrival measurements of the incident wave front at the nodes. Zooming in on the location of the firing point shows the scatter in the grid coordinates of the gun primaries due to the meteorological effects of wind and temperature variations on the propagation of sound in the atmosphere (**Figure 5, *right***). Ferguson et al. (2002) showed the results of localizing indirect weapon fire using acoustic sensors in an extensive series of field experiments conducted during army field exercises over many years. This work informed the full-scale engineering development and production of the Unattended Transient Acoustic Measurement and Signal Intelligence (MASINT) System (UTAMS) by the US Army Research Laboratory for deployment by the US Army during Operation Iraqi Freedom (2003-2011). This system had an immediate impact, effectively shutting down rogue mortar fire by insurgents (UTAMS, 2018).

Locating a Hostile Sniper's Firing Position

The firing of a sniper's weapon is accompanied by two acoustic transient events: a muzzle blast and a ballistic shock wave. The muzzle blast transient is generated by the discharge of the bullet from the firearm. The acoustic energy propagates at the speed of sound and expands as a spherical wave front centered on the point of fire.

The propagation of the muzzle blast is omnidirectional, so it can be heard from any direction including those directions pointing away from the direction of fire. If the listener is positioned in a direction *forward* of the firer, then the ballistic shock wave is heard as a loud sharp crack (or sonic boom) due to the supersonic speed of travel of the projectile along its trajectory. Unlike the muzzle blast wave front, the shock wave expands as a conical surface with the trajectory and nose of the bullet defining the axis and apex, respectively, of the cone (see **Figure 6, *top left***). Also, the point of origin of the shock wave is the detach point on the trajectory of the bullet (see **Figure 6, *top right***). In other words, with respect to the position of the receiver, the detach point is the position on the trajectory of the bullet from where the shock wave emanates. The shock wave arrives before the muzzle blast so, instinctively, a listener looks in the direction of propagation of the shock wave front, which is away from the direction of the shooter. It is the direction of the muzzle blast that coincides with the direction of the sniper's firing point.

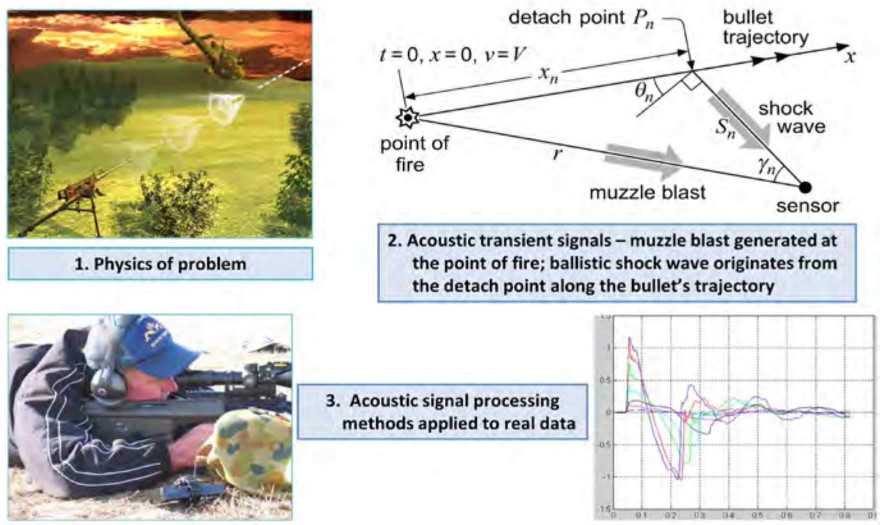

***Figure 6. Top: left,** image showing the conical wave front of the ballistic shock wave at various detach points along the trajectory of the supersonic bullet; **right,** source-sensor geometry and bullet trajectory. **Bottom: left,** source of small arms fire; **right,** "N"-shaped waveforms of ballistic shock waves for increasing miss distances. From Ferguson et al. (2007).*

Detecting the muzzle blast signals and measuring the time difference of arrival (time delay) of the wave front at a pair of spatially separated sensors provides an estimate of the source direction. The addition of another sensor forms a wide aperture array configuration of three widely spaced collinear sensors. As discussed in ***Estimating the Instantaneous Range of a Contact*** for submarines, passive ranging by the wave front curvature involves measuring the time delays for the wave front to traverse two pairs of adjacent sensors to estimate the source range from the middle sensor and a source bearing with respect to the longitudinal axis of the three-element array. Also, by measuring the differences in both the times of arrival and the angles of arrival of the ballistic shock wave and the muzzle blast enables estimation of the range and bearing of the shooter (Lo and Ferguson, 2012). In the absence of a muzzle blast wave (due to the rifle being fitted with a muzzle blast suppressor or the excessive transmission loss of a long-range shot), the source (**Figure 6, *bottom left***) can still be localized using only time delay measurements of the shock wave at spatially distributed sensor nodes (Lo and Ferguson, 2012). Finally, Ferguson et al. (2007) showed that the caliber of the bullet and its miss distance can be estimated using a wideband piezoelectric (quartz) dynamic pressure transducer by measuring the peak pressure amplitude and duration of the "N" wave (see **Figure 6**, ***bottom right***).

High-Frequency Sonar

Tomographic Imaging Sonar

The deployment of sea mines threatens the freedom of the seas and maritime trade. Sea mines are referred to as asymmetric threats because the cost of a mine is disproportionately small compared with the value of the target. Also, area denial is achieved with an investment many times less than the cost of mine-clearing operations.

Once a mine like object (MLO) is detected by a high-frequency (~100 kHz) mine-hunting sonar, the next step is to identify it. The safest way to do this is to image the mine at a suitable standoff distance (say 250 m away). The acoustic image is required to reveal the shape and detail (features) of the object, which means the formation of a high-resolution acoustic image, with each pixel representing an area on the object ~1 cm long by ~1 cm wide. The advent of high-frequency 1-3 composite sonar transducers with bandwidths comparable to their center frequencies (i.e., $Q \approx 1$) means that the *along*-range resolution $\delta r \approx 1$ cm. However, *real* aperture-receiving arrays have coarse *cross*-range resolutions of 1-10 m, which are range dependent and prevent high-resolution acoustic imaging. The solution is to synthesize a *virtual* aperture so that the cross-range resolution matches the along-range resolution (Ferguson and Wyber, 2009). The idea of a tomographic imaging sonar is to circumnavigate the mine at a safe standoff distance while simultaneously insonifying the underwater scene, which includes the object of interest. Rather than viewing the scene many times from only one angle (which would improve detection but do nothing for multiaspect target classification), the plan is to insonify the object only once at a given angle but to repeat the process for many different angles. This idea is analogous to spotlight synthetic aperture radar.

Tomographic sonar image formation is based on image reconstruction from projections (Ferguson and Wyber, 2005). Populating the projection (or observation) space with measurement data requires insonifying the object to be imaged from all possible directions and recording the impulse response of the backscattered signal (or echo) as a function of aspect angle (see **Figure 7, *left***). Applying the inverse Radon transform method or two-dimensional Fourier transform reconstruction algorithm to the two-dimensional projection data enables an image to be formed that represents the two-dimensional spatial distribution of the acoustic reflectivity function of the object when projected on the imaging plane (see **Figure 7, *bottom right***). The monostatic sonar had a center frequency of 150 kHz and a bandwidth of 100 kHz, so the range resolution of the sonar transmissions is less than 1 cm. About 1,000 views of the object were recorded so that the angular increment between projections was 0.35°. Distinct features in the measured projection data (see **Figure 7, *left***) are the sinusoidal traces associated with point reflectors visible over a wide range of aspect angles (hence, the term "sinogram"). Because the object is a truncated cone, which is radially symmetric, the arrival time is constant for the small specular reflecting facets that form the outermost boundary (rim at the base) of the object. **Figure 7, *top right***, shows a photograph of a truncated cone practice mine (1 m diameter base, 0.5 m high), which is of fiberglass construction with four lifting lugs and a metal end plate mounted on the top surface. **Figure 7, *bottom right,*** shows the projection of the geometrical shape of the object and acoustic highlights on the image plane. It shows the outer rim, four lifting lugs, and acoustic highlights associated with the end plate. Hence, tomographic sonar imaging is effective for identifying mines at safe standoff distances. Unlike real aperture sonars, the high resolution of the image is independent of the range.

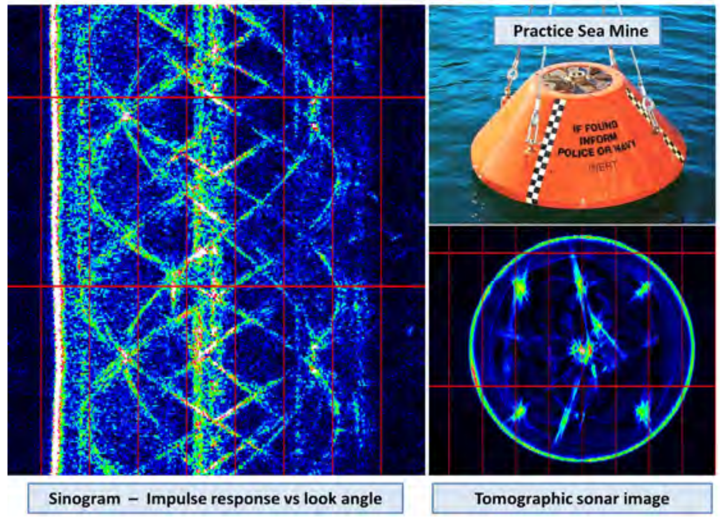

***Figure 7. Left:** two-dimensional projection data or intensity plot of the impulse response of the received sonar signal as a function of time (horizontal axis) and insonification angle (vertical axis). **Right: top,** photograph of the object; **bottom,** tomographic sonar image of the object. From Ferguson and Wyber (2005).*

Naval Base and Port Asset Protection

The suicide bombing attack of the USS COLE in October 2000 prompted the expansion of a program on the research and development of advanced mine-hunting sonars to include other asymmetric threats: fast inshore attack craft (FIAC), divers, and unmanned underwater vehicles. The detection, classification, localization, and tracking of these modern asymmetric threats were demonstrated using both passive and active sonar signal-processing techniques. The passive methods had already proven themselves in battlefield acoustic applications.

The rotating propeller of a FIAC generates a wake of bubbles that persists for minutes. When the wake is insonified by high-frequency active sonar transmissions, echoes are received from the entire wake, which traces out the trajectory of the watercraft. Insurgents rely on surprise and fast attack, so it is necessary to automate the detection, localization, and tracking processes because a FIAC attack can happen in as little as 20 s. A high-frequency high-resolution active sonar (or forward-looking mine-hunting sector scan sonar; see **Figure 8, *top***) was adapted to *automate* the detection, localization, tracking, and classification of a fast inshore craft in a very shallow water (7 m deep), highly-cluttered environment. The capability of the system was demonstrated at the HMAS PENGUIN naval base in Middle Harbour, Sydney.

A sequence of sonar images for 100 consecutive pings (corresponding to an overall observation period of 200 s) captured the nighttime intrusion by a small high-speed surface craft. **Figure 8, *bottom,*** shows the sonar image for ping 61 during the U-turn of the craft. The wake of the craft is clearly observed in the sonar image. The clutter in the sonar display is bounded by the wake of the craft and is associated with the hulls of pleasure craft and the keels of moored yachts. The high-intensity vertical strip at a bearing of 6° is due to the cavitation noise generated by the rapidly rotating propeller of the craft. In this case, the receiver array and processor of the sonar act as a passive sonar with cavitation noise as the signal. This feature provides an immediate alert to the presence of the craft in the field of view of the sonar. The sonar echoes returned from the wake (bubbles) are processed to extract accurate range and bearing information to localize the source. The number of false alarms is reduced by range normalization and clutter map processing, which together with target position measurement, target detection/track initiation, and track maintenance are described elsewhere (Lo and Ferguson, 2004). For ping 61, the automated tracking

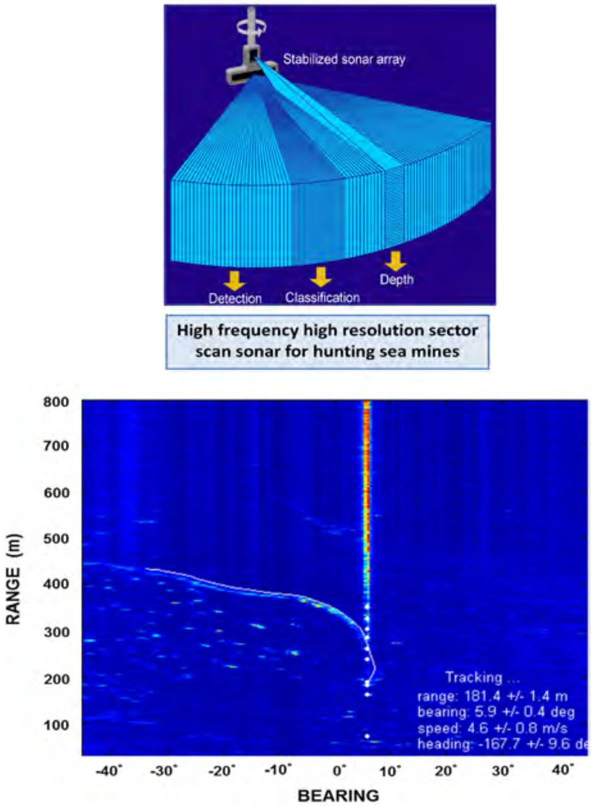

Figure 8. Top: *Sector scan sonar showing the narrow receive beams for detection and even narrower ones for classification.* ***Bottom:*** *sonar image for ping 61 as the fast surface watercraft continues its U-turn. From Ferguson and Lo (2011).*

processor estimated the instantaneous polar position of the craft (i.e., the end point of the wake) to be 181.4 m and 5.9°, the speed of the craft to be 4.6 m/s, and the heading to be −167.7°. Any offset of the wake from the track is caused by the wake drifting with the current.

The sonar is the primary sensor and, under the rules of engagement, a rapid layered response is now possible using a combination of nonlethal, less than lethal, and (last resort) lethal countermeasures.

Conclusion

The application of the principles and practice of acoustic systems science and engineering has improved the detection, classification, localization, and tracking processes for the Submarine Force, Land Force, and Mine Countermeasures Force, leading to enhanced situational awareness. Acoustic systems will continue to play a crucial role in operational systems, with new sensing technologies and signal-processing and data fusion methods being developed for the next generation of defense forces and homeland security.

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BioSketch

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