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THE EMERGENCE OF LOW–FREQUENCY ACTIVE ACOUSTICS AS A CRITICAL ANTISUBMARINE WARFARE TECHNOLOGY

For the three decades following World War II, the United States realized unparalleled success in strategic and tactical antisubmarine warfare operations by exploiting the high acoustic source levels of Soviet submarines to achieve long detection ranges. The emergence of the quiet Soviet submarine in the 1980s mandated that new and revolutionary approaches to submarine detection be developed if the United States was to continue to achieve its traditional antisubmarine warfare effectiveness. Since it is immune to sound-quieting efforts, low-frequency active acoustics has been proposed as a replacement for traditional passive acoustic sensor systems. The underlying science and physics behind this technology are currently being investigated as part of an urgent U.S. Navy initiative, but the United States and its NATO allies have already begun development programs for fielding sonars using low-frequency active acoustics. Although these first systems have yet to become operational in deep water, research is also under way to apply this technology to Third World shallow-water areas and to anticipate potential countermeasures that an adversary may develop.

HISTORICAL PERSPECTIVE

The nature of naval warfare changed dramatically following the conclusion of World War II when, in January 1955, the USS *Nautilus* sent the message, "Under way on nuclear power," while running submerged from New London, Connecticut, to San Juan, Puerto Rico. Spurred on by the increasing Cold War with the Soviet Union, the United States responded to the successful trials of the *Nautilus*, the world's first nuclear submarine, by initiating the rapid development of a succession of operational classes of nuclear attack submarines (SSN's). Just three years after the maiden voyage of the *Nautilus*, the mission of the nuclear submarine was further expanded when the Polaris Submarine Program was initiated. In July 1960, the USS *George Washington* (SSBN-598), successfully fired a ballistic missile from a submerged platform, thus establishing the strategic role of the nuclear submarine.

The Soviets sought to establish an early numerical superiority over the United States by launching the greatest submarine building program in history shortly after World War II. Two hundred and forty diesel–electric submarines were constructed by the Soviet Union between 1951 and 1957. These submarines could travel seventeen knots on the surface and fifteen knots submerged, to a range of 13,000 nautical miles. In addition, the Soviets quickly ended the U.S. monopoly on nuclear-powered submarines by announcing, on 21 July 1962, that they had nuclear submarines in action that had undergone successful exercises, including the firing of ballistic missiles from submerged positions.

In the decades that followed, both the United States and the Soviet Union significantly increased the size and capability of their submarine forces, and both countries have come to regard these submarines as principal components of their tactical naval forces, as well as their strategic arsenals. (Today, for example, the U.S. SSBN force provides over 5000 separate warheads, or about 50% of the U.S. strategic deterrent.) This increased capability of modern submarine forces allows for expanded missions and roles not possible during World War II. Current missions for U.S. SSBN and SSN forces include anti–surface-ship and antisubmarine warfare, strike and mine warfare, surveillance, reconnaissance, and strategic deterrence. Whereas the submarines of World War I and II were primarily a menace to surface shipping, modern submarines are the most important threat to a Navy's ability to control the seas and are a global threat to both sea- and land-based targets.

With the rise in the submarine's tactical importance, both the United States and the U.S.S.R. recognized the value of antisubmarine warfare (ASW). The Soviet Union developed an ASW strategy oriented toward defense of the homeland, shallow-water coastal security, and protection of Soviet SSBN bastion areas. In support of these objectives, the Soviets outfitted fleets of cruisers, destroyers, frigates, attack submarines, and aircraft to provide operational platforms for hosting tactical ASW sensors and weapons.

Because of its geographic isolation from trading partners, allies, and potential theaters of conflict, the United States necessarily invested in strategic, as well as tactical, ASW systems to maintain vital sea lanes of communication and to assure freedom of navigation in forward areas. In support of its perceived global ASW mission, the United

States developed formidable tactical ASW assets, and a system of highly capable passive sonar arrays for providing broad ocean surveillance in the North Atlantic and North Pacific basins. This Sound Surveillance System (SOSUS) supports the highest priority U.S. ASW missions, which include providing indications and warning of increased submarine activity (which could indicate preparation for the initiation of hostilities) and cueing tactical forces for follow-on operations, which may include final localization and attack.[1]

The U.S. submarine and ASW forces enjoyed significant tactical and strategic advantages over their Soviet counterparts for three decades after the conclusion of World War II. These advantages resulted from one major difference in the respective submarine designs—Soviet submarines, apparently engineered for performance (speed, depth, maneuverability), were significantly noisier than U.S. submarines. This difference in radiated noise levels could be directly translated into increased detection range, and hence, ASW mission effectiveness. Stefanick[1] estimates that in any given year the average Soviet submarine was 20 to 40 dB louder than U.S. submarines, resulting in as much as a factor of 100 difference in detection range by tactical sonars. The radiated signature levels of Soviet submarines were exploited by U.S. sonar designers, who relied heavily on passive acoustic sensors for detection of sound underwater. Passive sonars, consisting of single hydrophones or arrays of hydrophones, put no energy in the water; instead, they operate by detecting sounds emitted by the target. Tactical systems developed during this thirty-year period included air-dropped sonobuoys, hydrophone arrays towed from destroyers and frigates, and submarine hull-mounted and towed arrays. The two major U.S. surveillance systems, SOSUS and the Surveillance Towed Acoustic Sensor System (SURTASS), were also developed around the concept of a threat with high radiated signature levels.

During the 1960s and 1970s, the Soviets made incremental improvements in quieting their submarines, which because of advances in U.S. technology could be easily matched by evolutionary changes in U.S. ASW sensors. This picture began to change dramatically in the late 1970s. In 1978, the Soviet's *Victor III* attack-class submarine was introduced, with significantly lower radiated noise levels than any previous class of Soviet submarine. This advance was followed by even quieter classes of attack, cruise missile, and ballistic missile submarines. Using unclassified sources, Stefanick[1] has produced estimates of decreasing Soviet acoustic source levels (Fig. 1). He estimates that Soviet radiated signature levels dropped by 30 dB, or a factor of 1000, from 1975 to 1988. Depending on the specific oceanographic characteristics of the environment in which the submarine is operating, this could decrease surveillance ranges by thirtyfold to a thousandfold.

Recent political changes in the Soviet Union have resulted in a dramatic reduction in the perceived Soviet threat. The resultant decline in Soviet global influence is now viewed as increasing political instability in Third World areas. For this reason, U.S. military strategists have significantly increased the priority for addressing

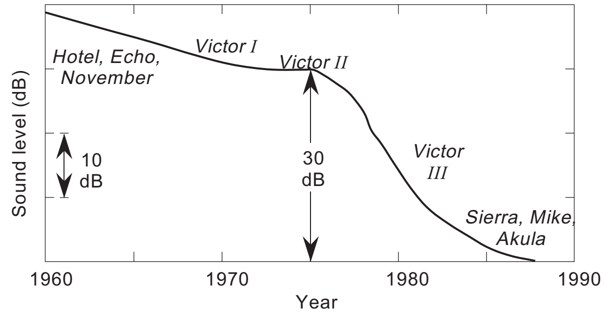


Figure 1. Estimates of the change in Soviet submarine-radiated broadband sound levels. (Reprinted, with permission, from Ref. 1, p. 287, Fig. A6–6. © 1987 by D. C. Heath and Company.)

Third World scenarios. In response to this change, new geographic areas, particularly shallow-water regions, and quiet diesel–electric submarines operating on batteries must be included in the ASW picture.

Decreases in radiated signature levels for Soviet submarines, the inclusion of Third World diesel–electric submarines operating on batteries, and commensurate decreases in ASW detection performance, now require the United States and its NATO allies to develop new sensor systems if they hope to maintain adequate performance in accomplishing traditional ASW missions. Unlike the 1950s, 1960s, and 1970s, however, when evolutionary improvements in sensors could keep pace with quieting efforts, revolutionary changes are now required in detection technology.

There are several generically different technology options that might be investigated. The possibility of utilizing nonacoustic phenomena in such fields as hydrodynamics, magnetics, optics, and radar has been aggressively pursued by the Navy. At the present time, however, it is not believed that operational concepts exploiting these phenomena can provide adequate detection ranges to support surveillance or moderate-range tactical requirements.[1,2] Exploitation of nontraditional passive acoustic signature components may extend the life of passive acoustics, but these techniques are also susceptible to sound-quieting efforts.

Although they do not operate covertly like passive sensors, active sonars have the advantage of providing their own energy for illuminating quiet targets. The active sonars used during World War II achieved only short detection ranges against German U-boats because of the high frequencies employed. Although the engineering designs of these sonars were made more manageable by the lighter, more compact high-frequency transducers, the long detection ranges associated with surveillance require lower operating frequencies because sound absorption in seawater is dependent on frequency. For this reason, low-frequency active acoustics (LFAA) is an area of high interest to the U.S. Navy today.

Responding to the changing undersea warfare environment, the Chief of Naval Operations (CNO) established a major program in 1985 to pursue alternatives to traditional passive acoustics. This initiative, the CNO Urgent ASW Research and Development Program (CUARP), placed a high priority on low-frequency active acoustics, and resulted in a research and development effort for resolving the critical issues associated with LFAA.[3,4] Critical Sea Test (CST) is a nonacquisition program chartered by the Office of the Chief of Naval Operations (OP-91) as part of the CUARP to support development programs in LFAA by resolving the key issues associated with system design and performance prediction. In 1986, APL was selected by the Navy (SPAWAR PMW-183) to be the lead laboratory for this effort. As a "tech-base" program, CST investigates the underlying science and physics associated with acoustic propagation in the ocean, reverberation from surface and bottom boundaries as well as biologics in the water column, source parameters and waveforms, and processing algorithms.

ACOUSTIC DETECTION OF SUBMARINES

There are two generic approaches for exploiting underwater sound for the detection of submarines. Passive acoustic systems listen, using hydrophones, for sounds generated (usually inadvertently) by the target. With passive systems, only one-way transmission through the ocean medium is involved (Fig. 2A). Active acoustic systems purposely generate sound using an underwater projector. These sound waves propagate through the ocean to the target, reflect or scatter from the target's hull, and then propagate through the ocean to the receiving hydrophones (Fig. 2B).

The performance of a passive acoustic system can be modeled mathematically using what is called the passive sonar equation. For convenience, this equation is written in decibel units. The passive sonar equation is written as

$$(SL - TL) - (NL - DI) = DT \ , \qquad (1)$$

where the source level, SL, the amount of sound radiated by the target, is the decibel equivalent of the power, sl; that is, $SL = 10 \log(sl)$. (Radiated sound is defined as the radiated intensity at one yard [~0.91 m] relative to the intensity of a plane wave of rms pressure 1 μPa, expressed in decibel units). The sound radiated by the target, traveling through the medium to the receiver, undergoes various propagation losses, called transmission loss (TL). The term ($SL - TL$) represents the intensity of target-emitted sound arriving at the receiver. The sonar must compete against background noise in attempting to detect the target. The level of noise in the ocean, as seen by a receiver with no spatial discrimination, is denoted by NL. Sonars that have spatial directivity (e.g., arrays of hydrophones), can reject noise that comes from nontarget directions. The amount of noise reduction is called the directivity index (DI). The left-hand side of Equation 1 is, therefore, equal to the difference between the signal level and noise level as seen by the receiver, referred to as the signal-to-noise ratio (SNR).

The background noise in the ocean that the receiver must compete against is a random process. The signal, as seen by the receiver, may also be random. The problem of detection therefore becomes a decision process in which the operator (or system) must decide whether a signal is present (signal and noise at the receiver), or absent (noise only). Detection theory (see Urick,[5] for example) provides a methodology for determining the SNR that is required to realize a specified probability of detection, Pd, and a specified false alarm probability, Pfa (i.e., deciding a target is present when only noise is present at the receiver). This signal-to-noise ratio, expressed in decibels, is called the detection threshold, DT.

Equation 1 is satisfied at the point where there is just enough signal-to-noise ratio for the target to be detected. In fact, the target is detected everywhere the signal-to-noise ratio at the receiver is greater than or equal to the detection threshold, that is, where the left-hand side of Equation 1 is greater than or equal to the right-hand side. The sonar equation can therefore be rearranged to include a new term, signal excess (SE), which is the excess (or shortfall) of signal-to-noise ratio required for detection:

$$SE = (SL - TL) - (NL - DI) - DT \ . \qquad (2)$$

Thus, detection occurs when $SE \geq 0$.

Derivation of the active sonar equation when noise-limited is similar to the procedure used for passive acoustics. With appropriate modification, Equation 1 becomes

$$(SL - TL_{ST} - TL_{TR} + TS) - (NL - DI) = DT \ . \qquad (3)$$

Here, SL is the amount of sound radiated by the sonar's own projector, rather than by the target. The acoustic waves must propagate from the source to the target, encountering one-way transmission loss (TL_{ST}), where the subscript ST indicates source to target. The ability of the target to reflect, or scatter, energy back to the receiver is called target strength (TS). Target strength is defined as the ratio, expressed in decibels, of the intensity of sound returned by the target at a distance of one yard to the intensity of sound striking the target from a distant source. After it is reflected from the target, the sound must again propagate through the medium from the target back to the receiver, encountering a second transmission loss, TL_{TR}. (The subscript TR indicates target to receiver.) The term ($SL - TL_{ST} - TL_{TR} + TS$) is, therefore, the signal level present at the receiver.

Unlike passive acoustics, there are two different potential sources of noise for an active acoustics system. As written, Equation 3 treats ambient noise (typically generated by shipping and wind/wave action) in the same manner as the passive sonar equation. For active systems, however, echoes can be generated by the rough ocean surface and bottom boundaries, as well as by fish or other biologics present in the water column. These sources of noise are referred to as surface, bottom, and volume reverberation. The total sound scattered back to the receiver by these sources of echoes is the reverberation level (RL). Although ambient noise is assumed to be isotropic (coming uniformly from all directions), reverberation may be highly directional (e.g., from seamounts, or schools of fish). For this reason, it may not be possible to define a meaningful omnidirectional reverberation level that is to be reduced by the spatial directivity of the receiver, DI. For example, consider the case where rever-

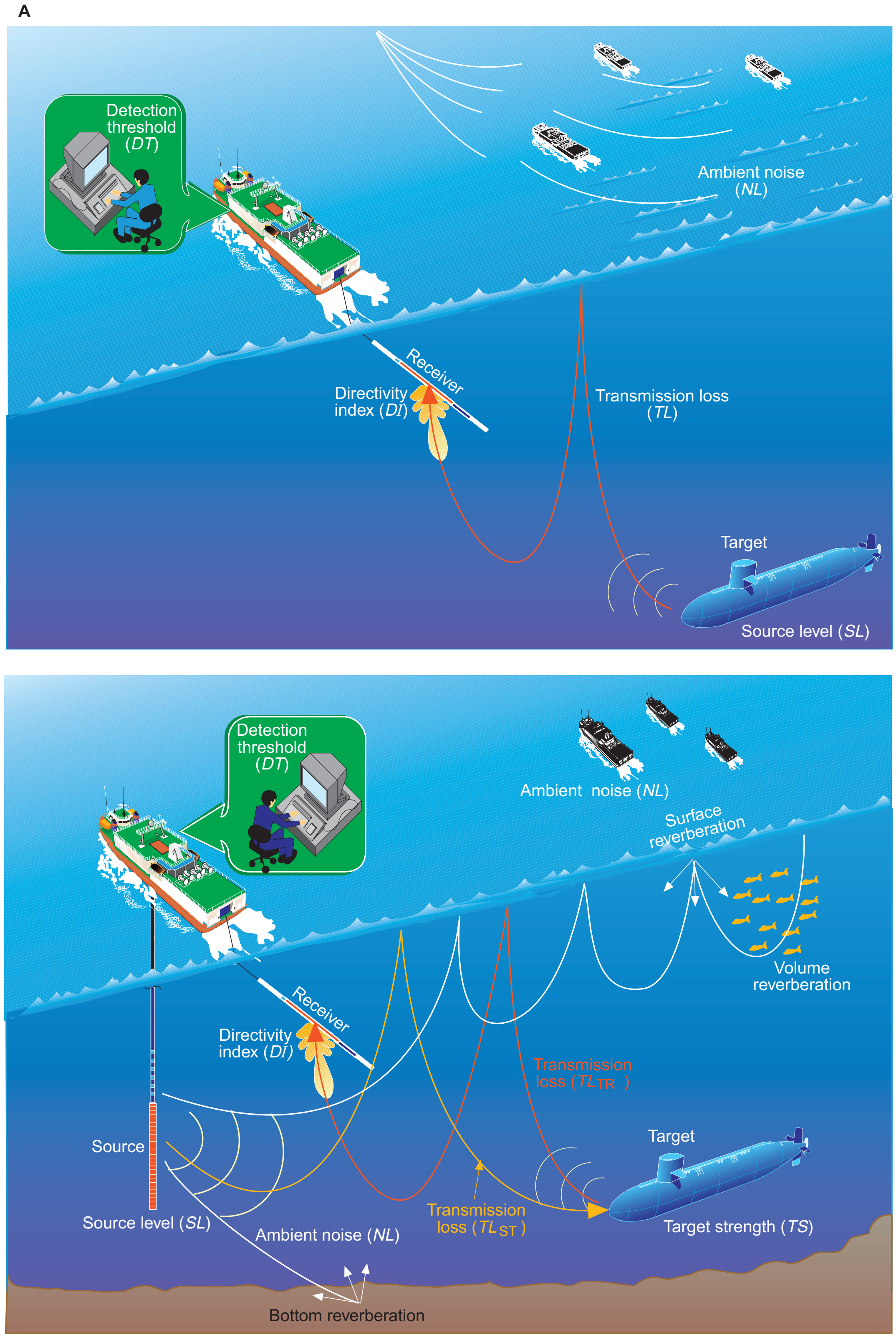


Figure 2. Elements of the sonar equation. **A.** The passive sonar equation mathematically describes the generation of sound from a target submarine, which propagates to a receiver and must then be detected in the presence of ambient noise. **B.** The active sonar equation mathematically describes the generation of sound from an acoustic source (as part of a sonar system), which propagates through the ocean medium producing echoes from target submarines, reverberation-backscattering from the rough ocean surface and bottom, and volume reverberation (e.g., from schools of fish). After the target echo propagates to the receiver, it must be detected in the presence of both ambient noise and reverberation.

beration level is measured with a single omnidirectional hydrophone, RL_{omni}, and then compare the results with the reverberation level as seen by an array of hydrophones with spatial directivity. If the reverberation field is truly isotropic, the array would uniformly reject the reverberation in all directions, and the receiver would see $RL_{omni} - DI$ as the effective noise level in any direction. On the other hand, if all the reverberation were coming from a single scatterer, such as a large seamount, the spatially directive receiver would see the level RL_{omni} in the direction of the seamount, and no reverberation in any other direction. Using $RL_{omni} - DI$ would be incorrect for this latter case for any direction. For a reverberation-limited environment, therefore, the term $(NL - DI)$ is replaced by an equivalent plane-wave reverberation level, RL, observed at the hydrophone terminals. Equation 3 then becomes

$$(SL - TL_{ST} - TL_{TR} + TS) - RL = DT \ . \quad (4)$$

As in Equation 1, the left-hand sides of Equations 3 and 4 represent the SNR, and the right-hand side is the detection threshold, or the SNR required to achieve the specified Pd and Pfa. Signal excess is defined analogously when noise-limited:

$$SE = (SL - TL_{ST} - TL_{TR} + TS) - (NL - DI) - DT \ . \quad (5)$$

When reverberation-limited, the equation becomes

$$SE = (SL - TL_{ST} - TL_{TR} + TS) - RL - DT \ . \quad (6)$$

Although simple calculations for very specific conditions can be performed by treating the sonar equation terms as single-valued quantities, in reality, all of these terms are complex functions of various parameters. The most important of these are generally frequency and range. By establishing frequency and range parameters for the sonar equation terms, the performance of a system can be investigated to determine such things as maximum detection range or optimum design frequency. The analysis that follows, although not intended to be all-inclusive or very precise, will provide some insight as to what system design parameters are consistent with the detection range requirements for various U.S. Navy missions.

To determine what source level is required to achieve detection at a particular range of interest, the noise-limited active sonar equation (Eq. 5) can be used to solve for SL, by setting SE equal to zero. An optimum design frequency (in the sense of minimum SL requirements) can also be determined by establishing the source level, as a function of frequency, that is required to achieve detection.

A simple model will be used to estimate transmission loss as a function of range and frequency. Transmission loss has two basic components: spreading loss, a geometrical effect representing the decreasing intensity of acoustic energy as sound spreads outward from the source; and absorption loss, caused by the conversion of acoustic energy into heat. In Figure 3 it can be seen that sound spreads spherically at short ranges and cylindrically at long ranges, owing to entrapment between the ocean surface and bottom boundaries. Because the surface area of a sphere increases as the square of the radius, $TL \rightarrow 1/R^2$ for short ranges. Similarly, at long ranges, $TL \rightarrow 1/R$, because the surface area of a cylinder varies linearly with radius. Assuming a representative deep-water environment, the effective transition range between spherical and cylindrical spreading can be chosen as one nautical mile, or two kiloyards (kyd). The spreading loss for ranges less than 2 kyd is then $10 \log(R^2)$ or $20 \log(R)$, where R is in kiloyards. For ranges greater than 2 kyd, the spreading loss due to cylindrical spreading is given by $10 \log(R/2 \text{ kyd})$. When combined with the initial spherical spreading loss term, this gives

$$\text{spreading loss} = 20 \log(2 \text{ kyd}) + 10 \log(R/2 \text{ kyd}) \ , \quad (7)$$

or

$$\text{spreading loss} = 66 \text{ dB} + 10 \log(R_{nm}) \ , \quad (8)$$

where R_{nm} is the range in nautical miles (one nautical mile is equal to 6080 ft). The absorption coefficient, α, in decibels per kiloyard, is based on work by Thorpe:[6]

$$\alpha = 0.1f^2/(1 + f^2) + 40 f^2/(4100 + f^2) + 2.75 \times 10^{-4} f^2 + 0.003 \ , \quad (9)$$

where f is the frequency in hertz.

The entire formula used for transmission loss is the sum of spreading and absorption losses (the absorption loss is the absorption coefficient times the range):

$$TL = 66 \text{ dB} + 10 \log(R_{nm}) + (\alpha R_{kyd}) \ , \quad (10)$$

or

$$TL = 66 \text{ dB} + 10 \log(R_{nm}) + (2\alpha R_{nm}) \ .$$

Target strength for a submarine is a complicated function of frequency, aspect, and the design parameters of the particular hull. A model for a simple cylinder will be employed in this discussion to provide a representation that is analytically manageable, but preserves enough detail to support the general conclusions of this analysis. The validity of this model decreases with off-beam aspect angle, because details of the hull structure are not included (e.g., sail, planes, the "turtleback" superstructure above the pressure hull, spherical endcaps, and internal structure such as bulkheads), and because only rigid geometric scattering is assumed.[5]

The formula for TS as a function of frequency and aspect angle for a finite cylinder is based on the work of Kerr:[7]

$$TS = (aL^2/2\lambda)(\sin \beta/\beta)^2 \cos^2\theta \ , \quad (11)$$

where a is the radius of the cylinder in yards, L is the length of the cylinder in yards, λ is the acoustic wavelength, θ is the aspect angle off-beam (normal to the cylinder), and

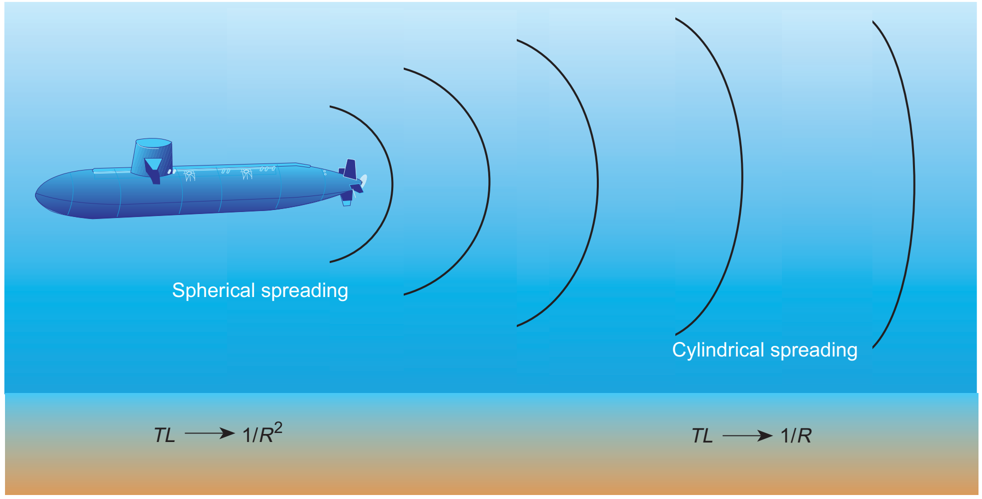


Figure 3. Characteristics of deep-water propagation. Sound radiated in deep water initially propagates in all directions, producing a spherically spreading wave front. At long ranges, the propagating sound becomes trapped between the ocean surface and bottom, resulting in a more nearly cylindrical wave front.

$$\beta = kL \sin \theta \ , \tag{12}$$

$$k = 2\pi/\lambda \ . \tag{13}$$

Equation 11 can be understood in terms of basic antenna theory, using Figure 4 as a guide. The first term in Equation 11, $aL^2/2\lambda$, provides the coherent mainlobe response of an array at normal incidence, modified to take the geometric shape of a cylinder into account. For angles off normal incidence, the effective length of the radiator is shortened to be its projection in the direction of viewing; that is, the length is multiplied by cos θ. Since this modification must be applied twice to account for both illumination and reradiation, the effective length of the radiator becomes $L^2\cos^2\theta$. The middle term in Equation 11, $(\sin \beta/\beta)^2$, is the beam pattern of a line array. In general, most energy is scattered in the specular direction, as shown in Figure 4, with backscattering being reduced by the sidelobes of the beam pattern. Here again, the beam pattern modification must be applied twice to account for both illumination and retransmission, which yields $(\sin \beta/\beta)^2$.

The scattering described by Equation 11 exhibits a complex dependence on frequency and aspect that is indicative of the target strength behavior of actual submarines. Figure 5 shows examples of this phenomenon at a frequency of 200 Hz for a 300-ft-long cylinder with a 30-ft diameter. Note the complex lobing structure present even in this simple model. This complex behavior can significantly complicate design studies for optimum sonar parameters. For this analysis, the simpler response at beam aspect will be used.

The noise level employed in this study is based on the classical work of Wenz,[8] which describes the levels of ship-generated and wind-generated ambient noise as functions of shipping density, wave height or sea state, and frequency. These curves are shown in Figure 6. Values for heavy shipping and sea state level 6 will be used, since an operational sonar must be designed to perform against expected worst-case conditions.

The gain of the receive array, or the directivity index, will be chosen consistent with the conclusions of Stefanick.[1] On the basis of theoretical models of the coherence of signal and noise in the deep ocean, and a survey of seventeen experimental data sets on coherence length, 20 dB was found to be an achievable level of *DI* at low frequencies, (that is, less than 1000 Hz). In this report, it will be assumed that this level is achievable across the entire band of interest. It should be noted that the engineering design of the array becomes more difficult at very low frequencies. For example, at 1000 Hz, a 20-dB array is approximately 250 feet long. The same gain array at 10 Hz would be 25,000 feet in length.

The last term of the sonar equation, detection threshold, will be based on the pioneering work of Peterson and Birdsall[9] on detection of a known signal in Gaussian noise:

$$DT = 10 \log(d/2T) \ , \tag{14}$$

where *d*, the detection index, is determined by the specified probability of detection and probability of false alarm,[5] and *T* is the duration of the waveform. Selecting typical values of $Pd = 90\%$ and $Pfa = 0.01\%$ gives $d \approx 25$. For both scientific and operational reasons, it is reasonable to assume a frequency dependence for *T*. The coherence time of the medium is longer for lower-frequency signals, and higher-frequency sonars operate at shorter ranges with higher waveform repetition rates. Waveforms for these sonars must be short in duration so they will not blank out short-range returns that might be received during the transmission interval. From operational experience, *T* will be chosen to be inversely proportional to frequency, with $T = 100$ s at 10 Hz, and $T = 1$ s at 1 kHz.

Using this methodology, the noise-limited active sonar equation (Eq. 3) was used to solve for source level as a function of range and frequency for a beam-aspect target modeled as a cylinder. The results are plotted in Figure 7. Each curve indicates the source level required for a sonar to achieve detection at the specified range, as a

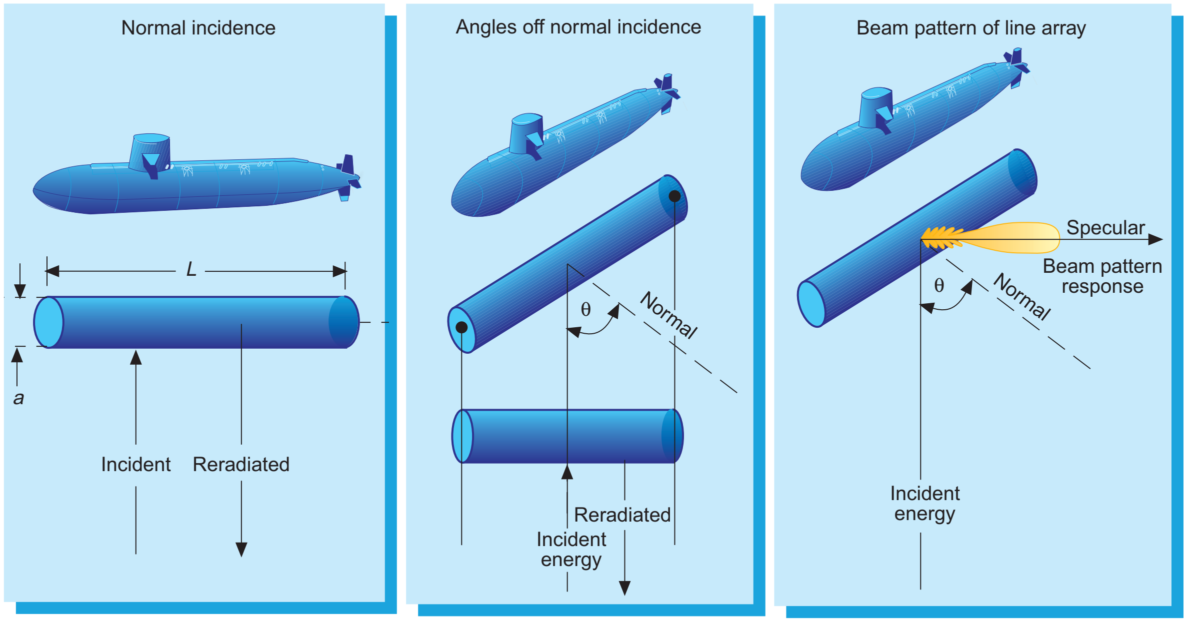


Figure 4. Cylinder model for target strength.

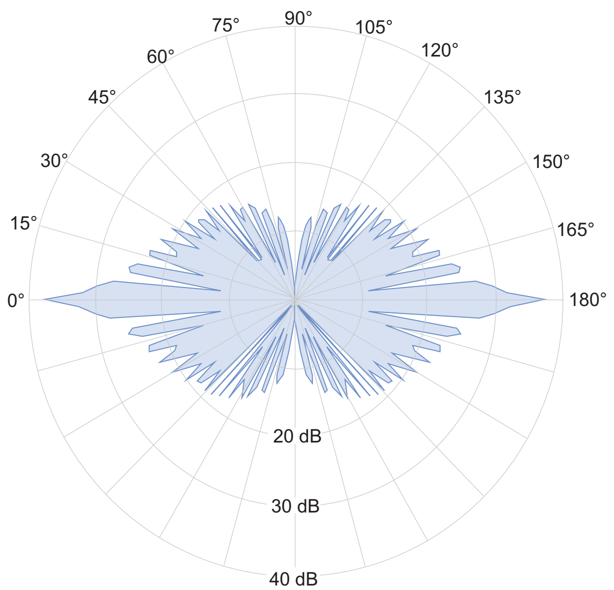


Figure 5. Target strength for a 300-ft by 30-ft cylinder as a function of off-beam aspect. A 200-Hz frequency was used.

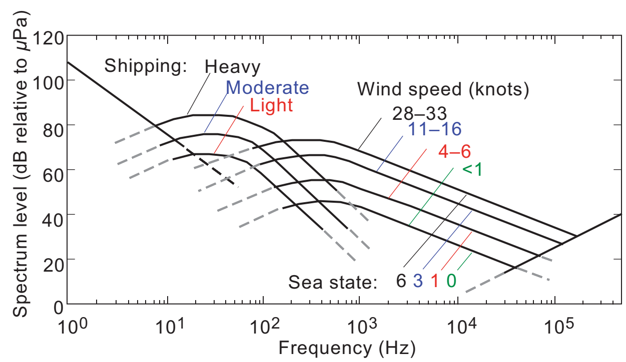


Figure 6. Average deep-water ambient noise spectra. Deep-water ambient noise is composed of shipping and wind/wave components. (Reprinted, with permission, from Ref. 5, p. 210, Fig. 7.5. © 1983 by McGraw-Hill.)

function of frequency. The lowest point on each curve corresponds to the "optimum" frequency, in the sense that it is the least amount of source power required for the system to achieve detection. This is a significant metric, in that size and weight constraints for the source are a major factor in determining system feasibility. For example, the current experimental LFAA system utilized in the CST program weighs approximately 100,000 pounds, and requires one megawatt of power-generation capacity. For every 3-dB increase in source level required, these numbers double. Obviously, size, weight, and power requirements are even more critical for an operational platform that must accommodate many requirements.

In Figure 7, note that optimum frequency becomes lower as the detection range increases. At very short ranges (one to three nautical miles), the optimum frequency occurs in the kilohertz portion of the spectrum, whereas at long ranges the optimum frequency drops into the hundreds of hertz. The upper-frequency cutoff is driven mainly by the absorption term in transmission loss. The steep roll-off of this function with frequency is so severe that the push to lower frequencies for longer ranges is a robust conclusion, even though there may be uncertainties in the other terms of the sonar equation for these frequencies.

The lower ends of the curves in Figure 7 rise more gradually as frequency decreases, owing to the shape of the ambient noise curves. Below 10 Hz, this rise becomes significantly steeper. Coupled with engineering considerations for extremely low frequency system designs (very long receive arrays and extremely large, heavy sources), the region below 10 Hz is probably not interesting for an operational system. Between the absorption cutoff at high frequencies and the uninteresting low-frequency regime below 10 Hz, the optimum system design frequency and the required source level are at issue, because the uncertainties in the sonar equation are great enough to shift the local *SL* minimum within these bounds. For this reason, CST and other research and development programs were initiated by the Navy to resolve uncertainties in the sonar equation parameters for low-frequency active sonars. The real situation is significantly more complicated than Figure 7 indicates. If the frequency response of a receive array were included (a 200-Hz array was arbitrarily selected), as well as a near-quartering target (40° off-beam), the result would be Figure 8. As can be seen, when more realism is built into the sonar equation, significant variability is introduced in the curve. Although general conclusions about the existence of an optimum design frequency lying between low-frequency noise and high-frequency absorption cutoffs remain valid, a best-design frequency is less obvious. Sonar engineers must necessarily understand detailed characteristics of each term in the sonar equation to produce designs that are effective against variations in the target and the ocean medium.

ASW PLATFORMS, SENSORS, AND MISSIONS

The U.S. ASW forces include a variety of acoustic sensors installed on air, surface, and subsurface platforms, as well as those at fixed geographic locations. These systems support Navy missions in broad ocean surveillance, detection, classification, localization, and prosecution. Figure 9 lists the major acoustic elements of antisubmarine warfare. Very short range acoustic sensors with detection ranges of a few kiloyards, such as mines, torpedoes, and air-deployed sensors, are typically utilized for final localization and prosecution. Intermediate detection ranges, from miles to tens of miles, are generally required for surface-ship ASW missions (such as area sanitization or Battle Group defense against the torpedo threat), and by attack submarines for counterdetection of threatening submarines. Currently, the ASW systems supporting these missions are composed of hull- and bow-mounted active and passive sonars and by tactical towed arrays. Surveillance ranges are necessarily hundreds of miles to be effective for broad ocean surveillance. The United States has both fixed and mobile large-aperture passive acoustic arrays in its surveillance inventory.

Developed in an era of noisy submarines, the U.S. ASW systems performed extremely well against the Soviet order of battle for which they were designed. Figure 9 indicates the range associated with each type of ASW system. Introduction of the quieter Soviet submarine, and the addition of Third World diesel–electric submarines to the inventory of possible threats, have significantly degraded the effectiveness of U.S. passive acoustic sensors. The impact of this on ASW missions can be seen in Figure 10. Short-range tactical missions are only modestly affected because of the reliance on high-frequency active acoustics as well as nonacoustic sensors (e.g., magnetic anomaly detection). Medium-range tactical missions can be more significantly impacted. The lack of an adequate passive sonar capability for surface-ship ASW operations will influence tactics and significantly degrade overall mission effectiveness for covert and longer-range operations. For high-speed and noncovert ASW operations, active sonars will continue to provide acceptable performance despite submarine noise reduction. Attack submarine operations, however, critically rely on the passive acoustic detection advantage possessed by U.S. nuclear submarines. This advantage has been diminishing against the quiet threat posed by these newer submarines as the U.S. strategy of countering larger numbers of hostile

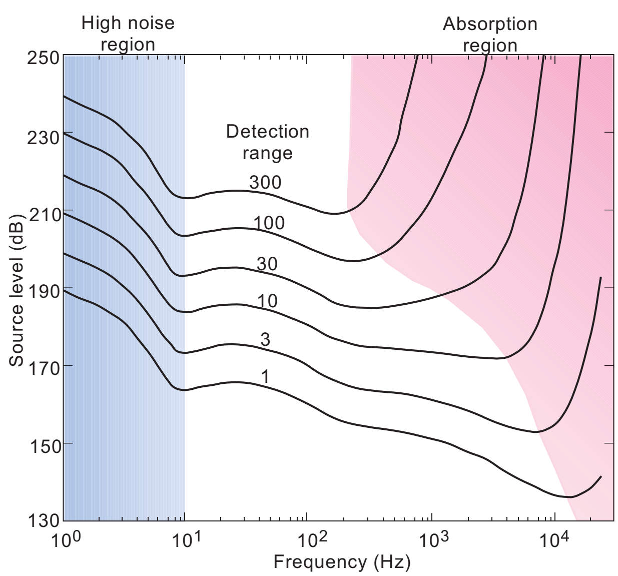


Figure 7. Required source level as a function of frequency. The minimum source level required for an active sonar to achieve a specified detection range (in nautical miles) corresponds to some optimum operating frequency. This frequency occurs in a region bounded by high ambient noise at low frequencies and high propagation losses due to absorption at high frequencies.

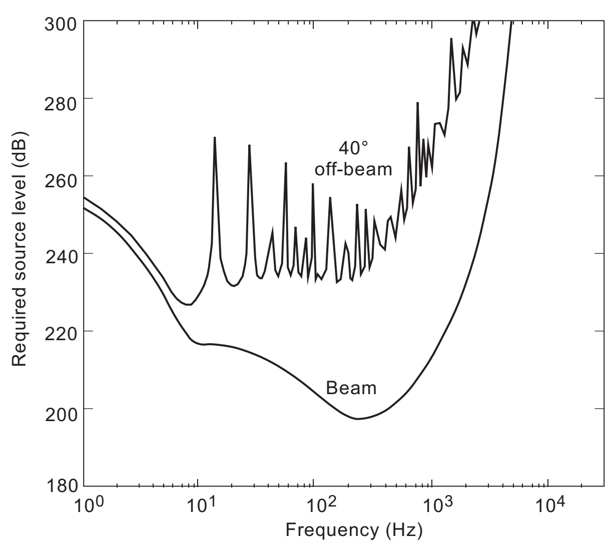


Figure 8. Comparison of source level requirements for beam and off-beam aspect targets. The required source level for an active sonar to achieve a detection range of 100 nautical miles is compared for the beam aspect target of Figure 7 and a near-quartering aspect target at 40° off-beam.

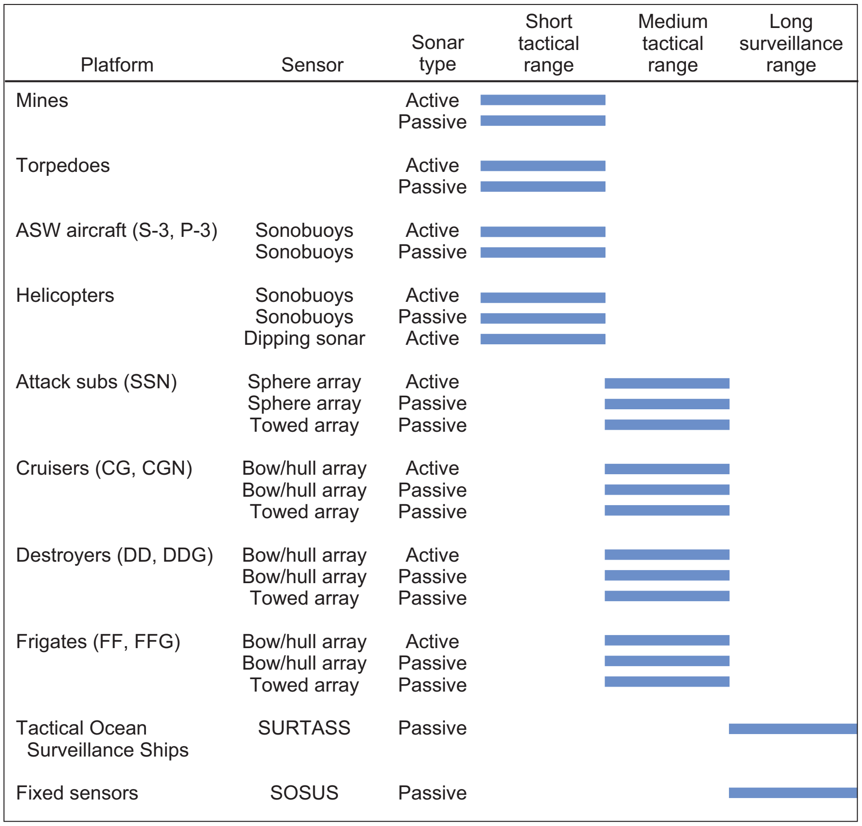


Figure 9. Performance of various antisubmarine warfare platforms against noisy submarines. Shaded blocks indicate good performance.

submarines with higher-quality submarines becomes less effective. The U.S. ASW mission most significantly affected by these quieter submarines, however, is long-range surveillance. Operational systems can no longer provide the long detection ranges necessary for broad ocean surveillance that have been provided by passive acoustics for the last thirty years.

To fill the gaps in long-range surveillance and medium-range tactical ASW operations left by the degrading performance of passive acoustic sensors, the Navy is investigating the utility of active acoustic systems. The elementary analysis provided previously showed a relationship between the optimum frequency band for designing active sonars and the required detection range (as plotted in Fig. 7). This relationship is depicted in Figure 11. High-frequency tactical active sonars have been, and will continue to be, effective systems for meeting short-range ASW requirements. The highest priority for Navy sonar development must now be given to those areas with poorest performance. As passive sonar performance degrades in the face of a quieter Soviet threat and Third World diesel–electric submarines, active sonars are therefore being pushed to lower frequencies to satisfy intermediate-range and long-range tactical and surveillance ASW requirements. The portion of the spectrum covered by low-frequency active sonars, however, roughly 1 kHz and below, has the highest degree of technical uncertainty. The size, weight, and power requirements of low-frequency sources have historically deterred definitive research and development efforts in this area.

CURRENT LFAA RESEARCH AND DEVELOPMENT EFFORTS

With the advent of the quiet-submarine threat, the United States and its allies have initiated numerous programs to develop low-frequency active operational sonars.[10,11] The Navy's CST program, begun in 1986, has been investigating all aspects of low-frequency active acoustics to support these development programs. The program is directing particular attention to the physics and underlying science associated with every aspect of the active sonar equation. This is made possible by unique program resources that can provide the source level, frequency range, receive array aperture, and processing power required to achieve an adequate signal-to-noise ratio for making definitive scientific measurements.

The at-sea activity of CST centers on the use of a dedicated test platform, the R/V *Cory Chouest*, shown in Figure 12. Under contract to APL, Edison Chouest Offshore of Houma, Louisiana, purchased a Norwegian North Sea pipe carrier, which was then converted into a research vessel, renamed the *Cory Chouest*. The ship has accommodations for seventy-one people, including twelve crew members, carries provisions for ninety days, and can hold 500,000 gallons each of diesel fuel and water. The three major scientific subsystems—source

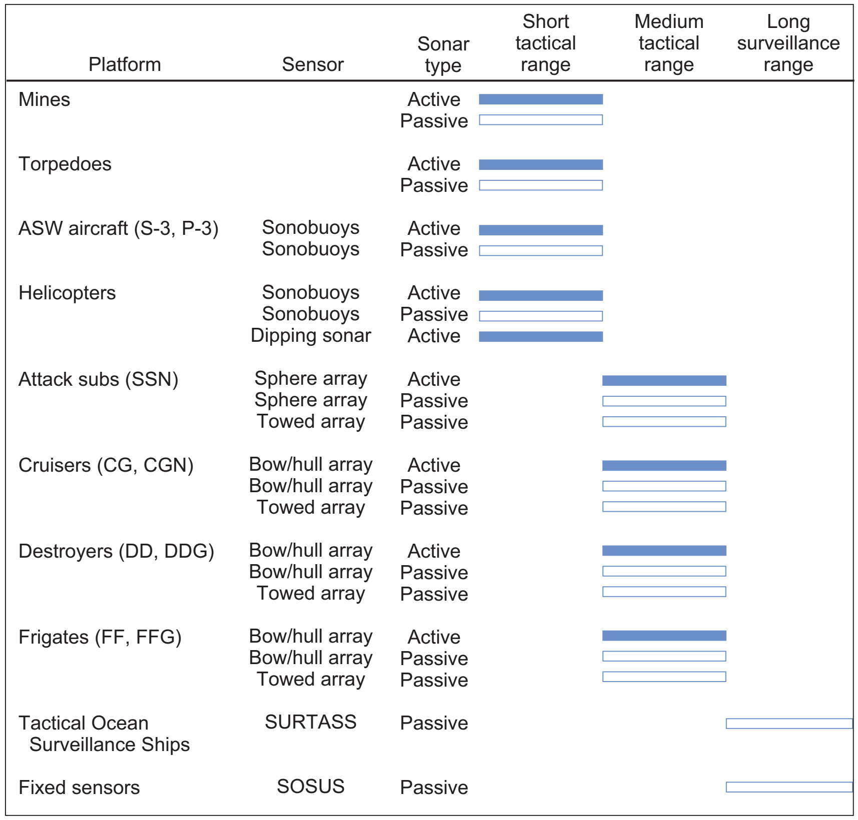


Figure 10. Performance of various antisubmarine warfare platforms against quiet submarines. Shaded blocks indicate good performance; open blocks indicate poor performance.

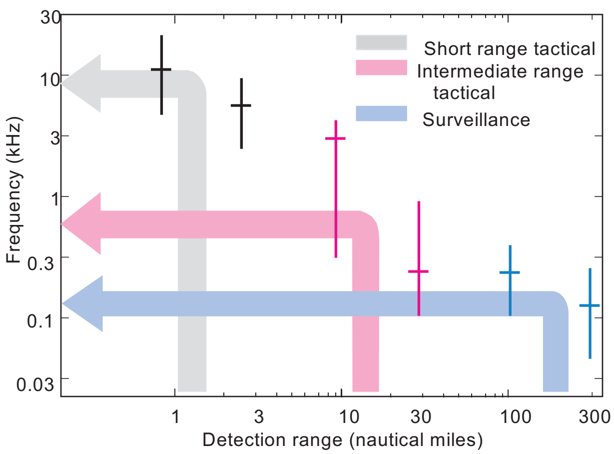


Figure 11. Relationship between operational mission and active sonar design frequency. The optimum frequencies for the six ranges plotted in Figure 7 are indicated by short horizontal bars. The vertical bars indicate the spread of frequencies that are within 3 dB of optimum.

arrays, receive arrays, and processors—make this the most advanced ASW platform in the world.

The acoustic-source subsystem consists of three source arrays suspended vertically in a 24-ft center well installed in the platform (see Fig. 13). Three arrays with different source element types are required to span the broad range of frequencies addressed by the program. Together, these three arrays weigh approximately forty-two tons in air and require one megawatt of power. The receive-array subsystem is constructed of three in-line, horizontal line arrays, which span the same range of frequencies as the source arrays and stream more than a mile behind the vessel.

The processor subsystem is composed of two interrelated computer-based systems. The first, a real-time processor that accepts data from the receive array, allows monitoring of data quality and pre-processes information that is then stored on nine-track "archive" tapes for further analysis. The second processor, designated the "off-line processor," allows analysts to play back archive tapes at a later time for scientific analysis. These processors, which have many times the central processing unit (CPU) power of even the most advanced operational ASW sea-based systems, allow for the "quick-look" analysis of data and reporting of results, which would otherwise take months or years of analysis.

The CST program has conducted five major at-sea experiments to date. So that the performance of operational systems can be evaluated in their actual operating environments, CST exercises occur in the Navy's highest-priority geographic areas. These have included the Norwegian Sea, the Icelandic basin, the Hatteras Abyssal Plain, the Mediterranean Sea, and the Gulf of Alaska. A typical CST exercise involves the *Cory Chouest* as the principal source/receiver platform, the R/V *Amy Chouest* (a sister ship) as a simulated target, an oceanographic research ship or surveying ship for environmental measurement support, fleet participation (guided missile destroyers and frigates),

Figure 12. The R/V *Cory Chouest.* Under contract to APL, Edison Chouest Offshore of Louisiana purchased the M/V *Tender Clipper*, a Norwegian North Sea pipe carrier. In just four months, APL and Chouest transformed this platform into the most advanced ASW research and development platform in the world. The aft deck was outfitted with engineering, instrumentation, and berthing spaces by the addition of the "APL module" (top). The finished vessel was then reflagged and renamed the R/V *Cory Chouest* (bottom).

and numerous maritime patrol aircraft. The Laboratory is responsible for the coordination of all participants and the successful execution of each test.

Although some degree of uncertainty exists in all six terms of the active sonar equation, over the last six years CST has concentrated on reverberation from the surface, bottom, and volume as the most important areas at issue for low-frequency active acoustics. Prior to CST, the resources did not exist to provide adequate frequency coverage, waveform control, and source level to acquire quality measurements of reverberation for scientific analysis. During the last five years, the CST program has made significant progress in these areas.

The classical treatment of surface reverberation has been to model the interaction of acoustic waves with the rough air/water boundary. Since the ocean wave spectrum is effectively continuous, this model predicts that sound will scatter by selecting that frequency component of the surface waves that allows backscattering from adjacent waves to add coherently and in phase. This diffraction grating model, shown in Figure 14, is referred to as Bragg scattering. An interesting feature of this model is that, owing to the motion of surface waves, a Doppler frequency shift of the backscattered energy is predicted. In 1962, Chapman and Harris[12] used explosive sound sources to measure surface scattering strengths at frequencies that were generally higher than those of interest for LFAA systems. Using data accumulated for a limited range of sea conditions over a period of two days, they developed an empirical formula for relating surface backscattering strength to frequency and wind speed (as an indirect measure of wave height). Because Doppler frequency cannot be measured with an impulsive waveform, the Bragg scattering model could not be tested. Nevertheless, this empirical relationship became the community standard for predicting surface reverberation levels, and has remained so for thirty years, even for LFAA frequencies, which must be extrapolated significantly below the measured data. Using the USNS *Mission Capistrano* in 1967, the Naval Research Laboratory (NRL) demonstrated the existence of Bragg Doppler lines at a single LFAA frequency, lending credibility to the Bragg model. In 1983, however, the Active Adjunct Undersea Surveillance (AAUS) program produced high-quality surface reverberation measurements, which indicated a large zero-Doppler component in the spectrum of the energy returned from the surface. This energy could not be accounted for in any existing model of the air/water interface.

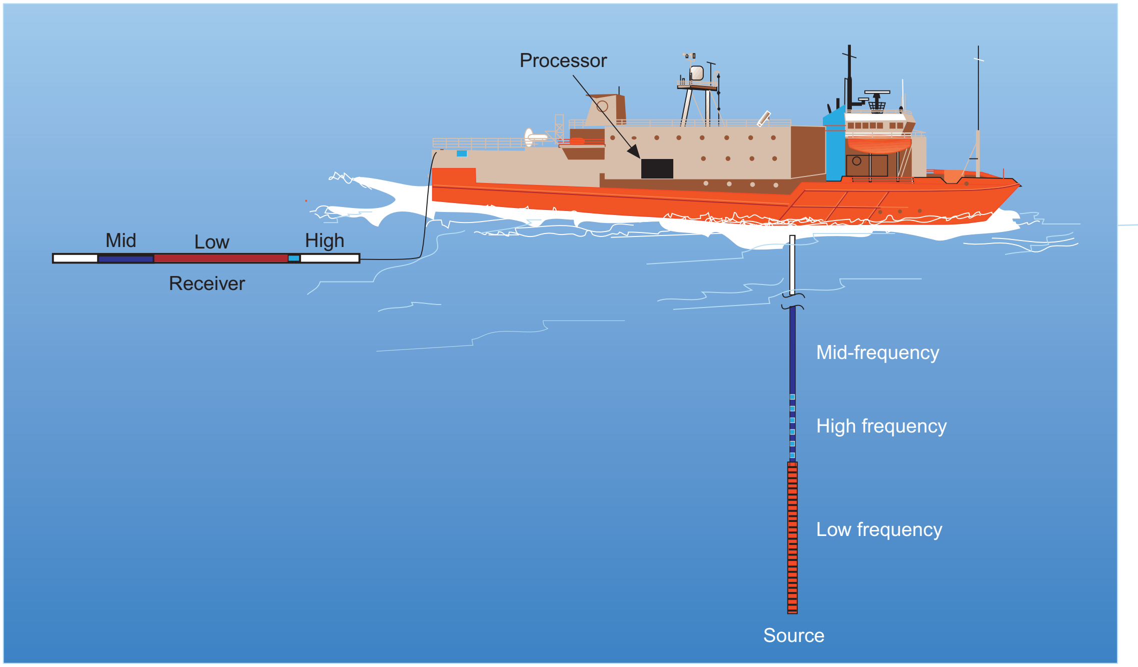


Figure 13. The R/V *Cory Chouest* with source, receiver, and processor subsystems. With its forty-two-ton vertical source array and mile-long horizontal receive array, the *Cory Chouest* can attain high levels of signal-to-noise ratio for definitive scientific measurements. The sophisticated processor subsystem, which has more central-processing-unit power than any other operational or research platform, can process all range and bearing cells in real time, and can provide archive tapes to an off-line processor for analysts to investigate the underlying science and physics of low-frequency active acoustics.

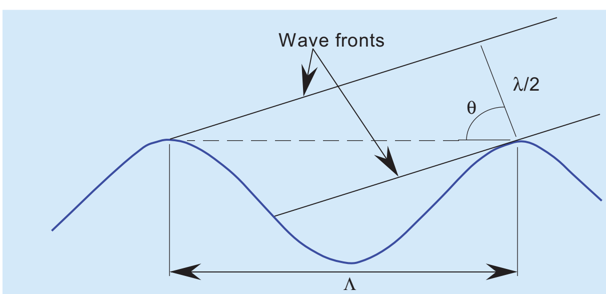


Figure 14. Diffraction grating or Bragg scattering. Bragg scattering occurs when the acoustic energy scattered by adjacent water crests adds coherently, and in phase. This occurs for only one component of the surface waves, that is, when the acoustic wavelength and the surface wavelength are related by $\lambda = 2\Lambda \cos \theta$, where λ is the acoustic wavelength and Λ is the water wavelength. Because each surface wave component travels with a specific velocity, there is a unique Doppler component added to the reflected acoustic energy.

Using the resources provided by the *Cory Chouest*, the CST program has been mounting an intense attack on the surface-scattering problem. Data acquired during four sea tests, which cover the entire LFAA band of interest and include sea states from flat calm to moderate gale conditions (28 knots), have shed some light on the nature of the physics behind the surface reverberation problem. Current theories treating air/water interface scattering predict only a slight dependence of scattering strength on wind speed. This is because the portion of the surface spectrum that contributes to Bragg scattering saturates at low wind speeds. As higher winds dump more energy into the surface, this energy goes into lower surface-wave frequencies, which do not contribute to Bragg scattering. Data taken by NRL (as part of the CST program) at the low end of the LFAA band, shown in Figure 15, clearly show a lack of wind-speed dependence. Data taken at the high end of the band, however, indicate significant dependence on wind speed, as evidenced in Figure 16. In addition, analysis of the CST database investigating the general dependence of scattering strength on wind speed and frequency shows that, for most of the band of interest, there is a threshold value of wind speed above which the scattering becomes dependent on wind and below which the scattering is independent of wind. This is graphically depicted in Figure 17. This led the CST investigators to hypothesize a second scattering mechanism, in addition to the air/water interface. This mechanism is now believed to be bubbles entrapped below the sea surface. This supposition is supported by the observation that the point where wind dependence becomes evident in the data corresponds to the beginning of white caps on the surface. A future CST test will be designed to measure the subsurface bubble layer and to quantify the impact on scattering.

Bottom backscattering has been classically treated[13] by applying Lambert's Law, developed in optics to model the backscattering of light from a rough surface. Bottom scattering can be significantly more complicated, however, and can include several mechanisms: scattering from the water/sediment interface; refraction through sediment layers and scattering from inhomogeneities in the sediment;

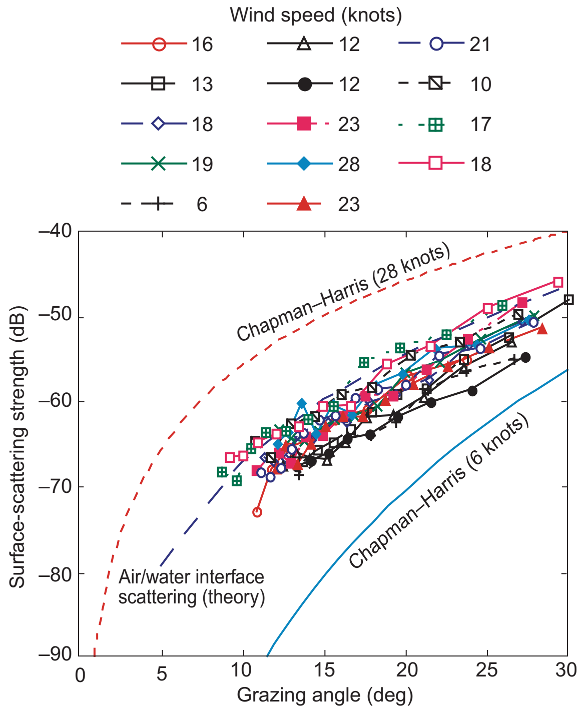


Figure 15. Surface-scattering strength versus grazing angle at low LFAA (low-frequency active acoustics) frequencies. At the low end of the LFAA frequency band, Critical Sea Test data show little dependence on wind speed and agree reasonably well with air/water interface scattering theories. The solid curve indicates the classical Chapman–Harris curve at six knots; the short-dashed curve shows the Chapman–Harris curve at twenty-eight knots. A projected curve based on air/water interface scattering theory is shown by the long-dashed curve.

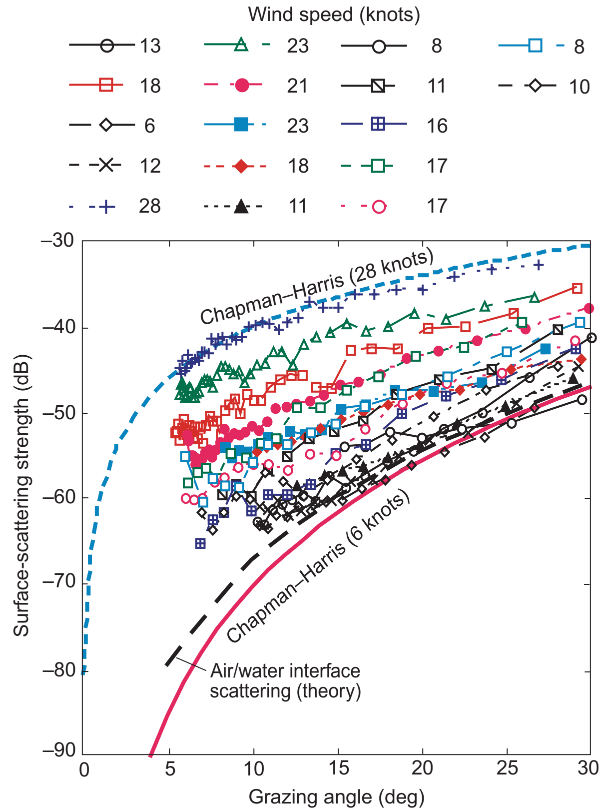


Figure 16. Surface-scattering strength versus grazing angle at high LFAA (low-frequency active acoustics) frequencies. At the high end of the LFAA frequency band, Critical Sea Test data agree with the classical Chapman–Harris empirical curves between twenty-eight and six knots and show significant wind speed dependence. The profound difference between this curve and the curve in Figure 15 suggests the existence of two different scattering mechanisms.

and scattering from the interface between the sediment and the hard rock "basement." Data taken as part of CST by the Naval Underwater Systems Center, in fact, exhibit scattering from multiple mechanisms. Figure 18 shows a distinct transition from scattering at the water/sediment interface to scattering within the sediment when the grazing angle passes through the "critical angle." The CST database is being used to investigate these scattering mechanisms and to determine their dependence on the geoacoustic characteristics of the bottom.

Volume reverberation is produced by scattering within the body of the ocean and is caused by biological organisms. Because the measured dependence of volume-scattering strength on frequency in the kilohertz region shows a strong falloff below several kilohertz (Fig. 19), volume reverberation was believed by many not to be a problem at LFAA frequencies.[5] The CST series of sea tests, however, has repeatedly shown that volume reverberation is a significant noise mechanism that must be taken into account in system design for all but the lowest LFAA frequencies. For example, in CST 1, measurement of surface-scattering strengths in high seas was precluded by volume scattering from dense schools of blue whiting. For most of the spectrum of interest, this volume scattering is the limiting noise mechanism that a sonar must be designed to overcome. Modeling and understanding the levels of volume reverberation seen in CST exercises have been very successful. During each CST exercise the scattering strength of biologics is measured using explosive sound sources, and a specially designed vertical line array of hydrophones is used to measure the backscattered energy. Using an acoustic propagation model, the scattering strengths obtained by this technique are then used to predict distant reverberation from biologics. Figure 20 shows the excellent agreement between the predictions and measurements, providing evidence that the distant reverberation seen here is indeed volume scattering.

FUTURE DIRECTIONS IN LFAA SONAR DEVELOPMENT

Since emphasis has been placed on the Soviet threat for the last forty years, Navy research and development in acoustics has concentrated heavily on countering the nuclear submarine in deep-water areas. Research in LFAA, including CST, has also been concentrated on deep-water areas. If current geopolitical trends continue, and the U.S. Navy increases the priority of Third World security issues, the research and development community will be designing sonars to meet new threats (e.g., diesel–electric submarines) operating in areas that differ significantly from the open ocean. In particular, most Third World scenarios envision the conduct of ASW operations in

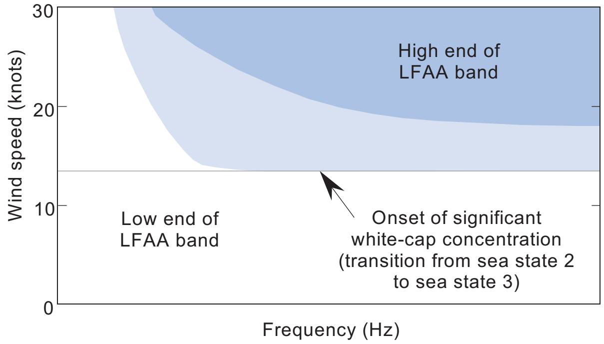
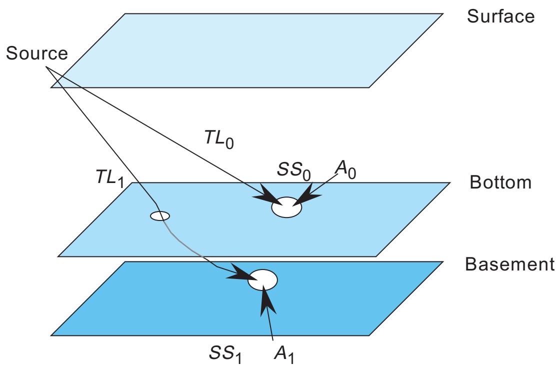


Figure 17. Summary of the wind and frequency dependence of Critical Sea Test surface scattering strength measurements. At the low end of the LFAA (low-frequency active acoustics) band there is no wind speed dependence, very slight frequency dependence, and surface scattering strength is generally consistent with or slightly above that predicted by perturbation theory. At the high end of the LFAA band, wind speed and frequency dependence is similar to that predicted by Chapman and Harris,[12] and an additional scattering mechanism (possibly bubble plumes) is required to explain observations of total scattering. In the intermediate range, there is an ill-defined (variable) dependence of scattering strength on wind speed and frequency, and a transition from air/water interface scattering to another mechanism.



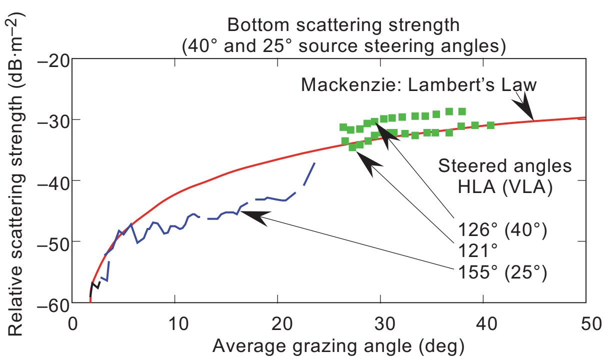


Figure 18. Bottom scatter results from Critical Sea Test (CST) data. Bottom backscattering is a complicated process, owing to the presence of multiple scattering mechanisms. The CST data shown here, taken in the Gulf of Alaska, show a change in scattering mechanism at about 25° grazing angle. Above 25°, energy enters into the bottom sediment and probably scatters from the rock basement (A_1). Below 25° (the critical angle), energy reflects and scatters at the water/bottom interface (A_0). TL_0 and TL_1 indicate transmission loss and SS_0 and SS_1 indicate scattering strength below and above 25°, respectively. On the right-hand side of the figure, angles for the horizontal line array (HLA) are given, with angles for the vertical line array (VLA) given in parentheses.

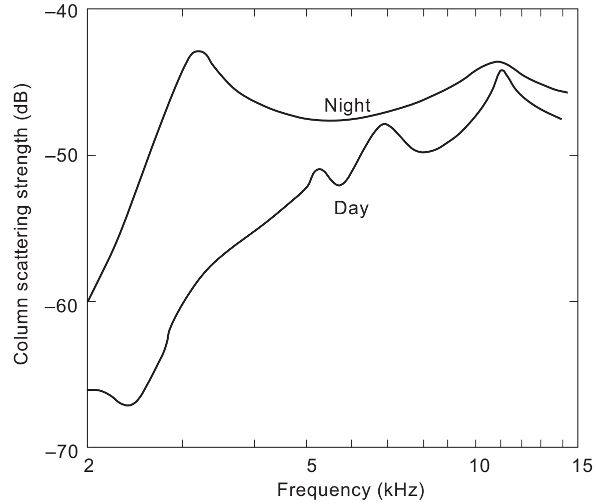


Figure 19. Volume scattering strength for high frequencies. Volume scattering over a column from 850 m to the surface (taken from Ref. 14) is plotted for an area between Nova Scotia and Bermuda. Because operational active sonars function at high frequencies, most scattering strengths were historically measured in the kilohertz region of the acoustic spectrum. Extrapolations of these measurements taken prior to Critical Sea Test led many to believe, incorrectly, that volume scattering was not a problem for low-frequency active systems. (Reprinted, with permission, from Ref. 5, p. 260, Fig. 8.15. © 1983 by McGraw-Hill.)

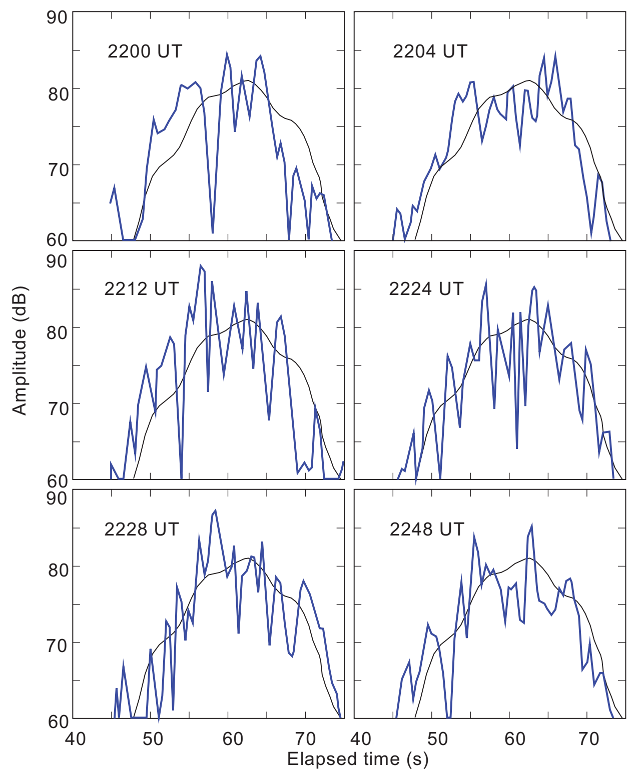


Figure 20. Measurements of volume reverberation by Critical Sea Test. The Critical Sea Test program utilizes several techniques to determine the sources of distant reverberation. In these plots, distant reverberation (black curves) is compared to model predictions (blue curves), using measured volume scattering strengths as input. Investigations like these have shown that volume scattering must be taken into account for most LFAA (low-frequency active acoustics) system designs.

shallow and restricted waters. To accommodate this change, the U.S. Navy will have to develop new operations and tactics, as well as new sensor and weapons technologies.

Phase 1 of the CST program (1986–1990) concentrated on deep-water issues related to the design of sensors and systems for countering the Soviet threat. Phase 2 of CST (1991–1996) will emphasize shallow-water issues, as well as acoustic warfare. In anticipation of the use of LFAA by many countries, the development of acoustic support measures, countermeasures, and counter-countermeasures is envisioned. Acoustic warfare considerations, similar to the development of electronic warfare for radar, must be built into sonar designs at the earliest stage possible to prevent the rapid obsolescence of LFAA systems.

As lead laboratory for the CST program, APL is responsible for spearheading the research that will lead to revolutionary changes in the way the U.S. Navy conducts antisubmarine warfare. With the answers provided by CST and other LFAA efforts in which the Laboratory is involved, new technologies will emerge that will be robust against the full spectrum of threats to the U.S. Navy.

REFERENCES

[1]Stefanick, T., *Strategic Antisubmarine Warfare and Naval Strategy*, Lexington Books, D. C. Heath and Company, Lexington, Mass. (1987).

[2]Winokur, R. S., and Dorman, C. E., "Antisubmarine Warfare and Naval Oceanography," *Oceanus* **33**(4), 20–30 (Winter 1990–91).

[3]White, S., *CNO Urgent ASW R&D Task Development,* CNM (MAT-08), 3900 Ser MAT-08/ASW (1985).

[4]Watkins, J. D., *CNO Urgent ASW R&D Program,* Ser 00/6U300181 (16 Jun 1986).

[5]Urick, R.J., *Principles of Underwater Sound*, 3rd Ed., McGraw-Hill, New York (1983).

[6]Thorpe, W. H., "Analytic Description of the Low Frequency Attenuation Coefficient," *J. Acoust. Soc. Am.* **42**(1), 270 (1967).

[7]Kerr, D. E. (ed.), "Propagation of Short Radio Waves," in *MIT Radiation Laboratory Series,* Vol. 13, McGraw-Hill, New York, pp. 445–469 (1951).

[8]Wenz, G. M., "Acoustic Ambient Noise in the Ocean: Spectra and Sources," J. *Acoust. Soc. Am.* **34**(12), 1936–1956 (1962).

[9]Peterson, W. W., and Birdsall, T. G., *The Theory of Signal Detectability,* Univ. Mich. Eng. Res. Inst. Rep., 13 pp. (1953).

[10]Lok, J. J., "Active Revolution in ASW Sonars," *Jane's Defence Weekly* (20 Jul 1991).

[11]Starr, B., "ASW: Fighting to Keep the Edge," *Jane's Defence Weekly* (7 Apr 1990).

[12]Chapman, R. P., and Harris, J. H., "Surface Backscattering Strengths Measured with Explosive Sound Sources," *J. Acoust. Soc. Am.* **34**(10), 1592–1597 (1962).

[13]Mackenzie, K. V., "Bottom Reverberation for 530- and 1030-cps Sound in Deep Water," *J. Acoust. Soc. Am.* **33**(11), 1498–1504 (1961).

[14]Chapman, R. P., and Marshall, J. R., "Reverberation from Deep Scattering Layers in the Western North Atlantic", *J. Acoust. Soc. Am.* **40**(2), 405–411 (1966).

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