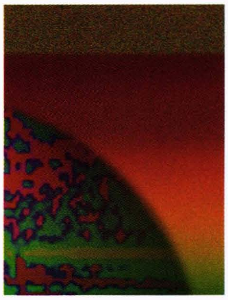

Twinline Array Development and Performance in a Shallow-Water Littoral Environment

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A towed two-line passive acoustic sensor with a horizontal aperture has demonstrated improved detection, noise performance, and reverberation rejection during recent at-sea testing and is thus an effective alternative to single-line array systems, particularly in a shallow-water environment. This recently developed sensor, referred to as the Twinline array, consists of two line arrays separated in the horizontal plane, a towing subsystem, and a shipboard processing suite. Towing characteristics and acoustic and detection performance were assessed in 1994 during three at-sea tests. The tests disclosed median noise gains of 25 dB or more over wide frequency bands and backlobe rejection ratios of up to 40 dB. Reverberation measurements with explosive sources revealed left–right rejection ratios exceeding 20 dB. Continued sea testing in 1995 will further manifest Twinline's effectiveness to the Fleet in passive and active scenarios.

INTRODUCTION

With the end of the Cold War, antisubmarine warfare has evolved from deepwater detection of nuclear-powered submarines to shallow-water detection of diesel/electric-powered submarines. The changes in the threat and operating environments have prompted modifications in the sensors used to detect hostile submarines. Shallow-water operation requires shorter sensors, which have less gain, to protect array hardware from dragging on the bottom. Shallow water also implies a highly directional noise field resulting from the nearness of shipping lanes. The Twinline array was designed to provide high gain in a directional noise field without resorting to an extremely long sensor.

Current single-line passive array sonar systems are not well suited to perform in shallow-water environments. Typical single-line surveillance passive array systems are extremely long and consequently have the advantage of high gain to resolve the directional noise field; however, they have a left–right ambiguity problem because of a lack of horizontal aperture.[1] In an area of high shipping density, the ambiguity problem creates look directions with noise interference, which limits detection of weaker targets. Active sonars can also be used to detect diesel/electric submarines, but detection ranges are restricted by the receiving system's gain and reverberation rejection.

With sufficient reverberation rejection, two-line passive towed sensors, such as Twinline, can be employed to receive active signals. The Twinline system overcomes the left–right ambiguity problem through multiple arrays in the horizontal plane. A high-gain horizontal aperture also helps to separate the noise field into noise sources and noise holes (quiet bearings). The Twinline sensor employs two line arrays towed parallel to the sea surface to resolve bearing ambiguity and the horizontal noise field. To complement the Twinline arrays, a towing subsystem to maintain horizontal separation and a processing subsystem for beam formation and display of the acoustic data were designed and installed. The Twinline beam-forming process is highly susceptible to line-to-line separation and slip (longitudinal offset) errors. To estimate shape accurately, the Twinline array employs a high-frequency shape measurement system to determine real-time line-to-line separation and slip at five points along the acoustic aperture. The entire Twinline system makes extensive use of existing Surveillance Towed Array Sensor System (SURTASS) array hardware and commercial off-the-shelf processing hardware.

The Twinline sensor was extensively sea tested in 1994 and will continue to be tested during 1995. Hydrodynamic trials were undertaken in January and June 1994 to determine towing stability and to develop system deployment and retrieval procedures. Engineering shakedowns of the array, towing subsystem, and processing suite were conducted in July and August of the same year and allowed the developers and scientists to optimize system performance. The Twinline system was deployed to the Adriatic Sea in September 1994 and participated in a Fleet antisubmarine warfare exercise, SHAREM 111 (Ship Antisubmarine Warfare Readiness/Effectiveness Measuring). During this exercise, the system demonstrated left–right rejection ratios up to 37 dB and median noise gains of 25 dB or more. This article will discuss the Twinline sensor system and its performance in relation to that of the single-line array, including noise gain, left–right rejection ratio, and reverberation rejection measurements.

TWINLINE SYSTEM DESCRIPTION

The Twinline system, as shown in Fig. 1a, can be thought of as three subsystems: the line arrays, the towing hardware, and the shipboard processing subsystem. The line arrays comprise the modular mechanical and telemetry systems depicted schematically in Fig. 1b. Each line array, which consists of 11 acoustic modules, is 3.5 in. in diameter and 81 wavelengths long at the highest operating frequency. The functions of the acoustic module, the basic building block of a towed array, are to house the acoustic and nonacoustic sensors and related electronics, to provide mechanical strength for towing, and to hold the fill fluid, which makes the whole module neutrally buoyant in seawater. Six types of modules are used in the array, including two types of acoustic modules, three nonacoustic modules, and a vibration isolation module (VIM). The acoustic aperture is formed from high-frequency acoustic modules, which contain 18 acoustic channels, and high-frequency adapter modules, which include 6 channels and a nonacoustic sensor station. Nonacoustic sensor stations are situated forward and aft of the acoustic aperture in the forward nonacoustic sensor (FNAS) module and the aft nonacoustic sensor (ANAS) module. Shape measuring unit (SMU) pingers and receiving hydrophones are also installed in all nonacoustic sensor stations. A non-acoustic sensor station (without SMU) is located at the forward end of the array in the nose cone module. The VIM attenuates unwanted energy caused by vortex shedding from the tow cable and aft drogue before the energy reaches the acoustic aperture.

The array's mechanical construction is identical to a high-frequency SURTASS module chassis. Three wire rope strength members absorb the hydrodynamic loads. Plastic spacers distributed periodically throughout the array protect the internal array components as they are reeled on and off the shipboard winch. For protection, the module chassis is encased in a nonreinforced polyurethane hose and filled with fluid and open-cell foam.

Each line array has its own telemetry system and transmits its data to the ship through individual coaxial cables. The telemetry system uses two coaxial cables: one for data and one for the clock. The data cable has 584 14-bit time slots, each time slot containing data from one acoustic sensor or 16 nonacoustic sensor data channels time-domain-multiplexed into a single time slot. The clock cable provides system timing and command information to acoustic and nonacoustic data transmitters located throughout the array and receives its command information from the shipboard receiver via two dedicated lines: the downlink and the synchronization coax.

Command information from the telemetry receiver unit (TRU) is received by the line synchronization enclosure located in the ANAS module and retransmitted to the clock coax. The use of a shipboard master clock, to which both line synchronization enclosures are slaved, ensures simultaneous sampling between the two arrays.

Four pressure-compensated hydrophones wired in a series-parallel configuration to a preamplifier gain select amplifier (PGSA) sense acoustic signals. Fabrication cost for the PGSA is kept low by encasing the printed circuit board in hard potting to withstand hydrostatic pressure at sea. The PGSAs, which have

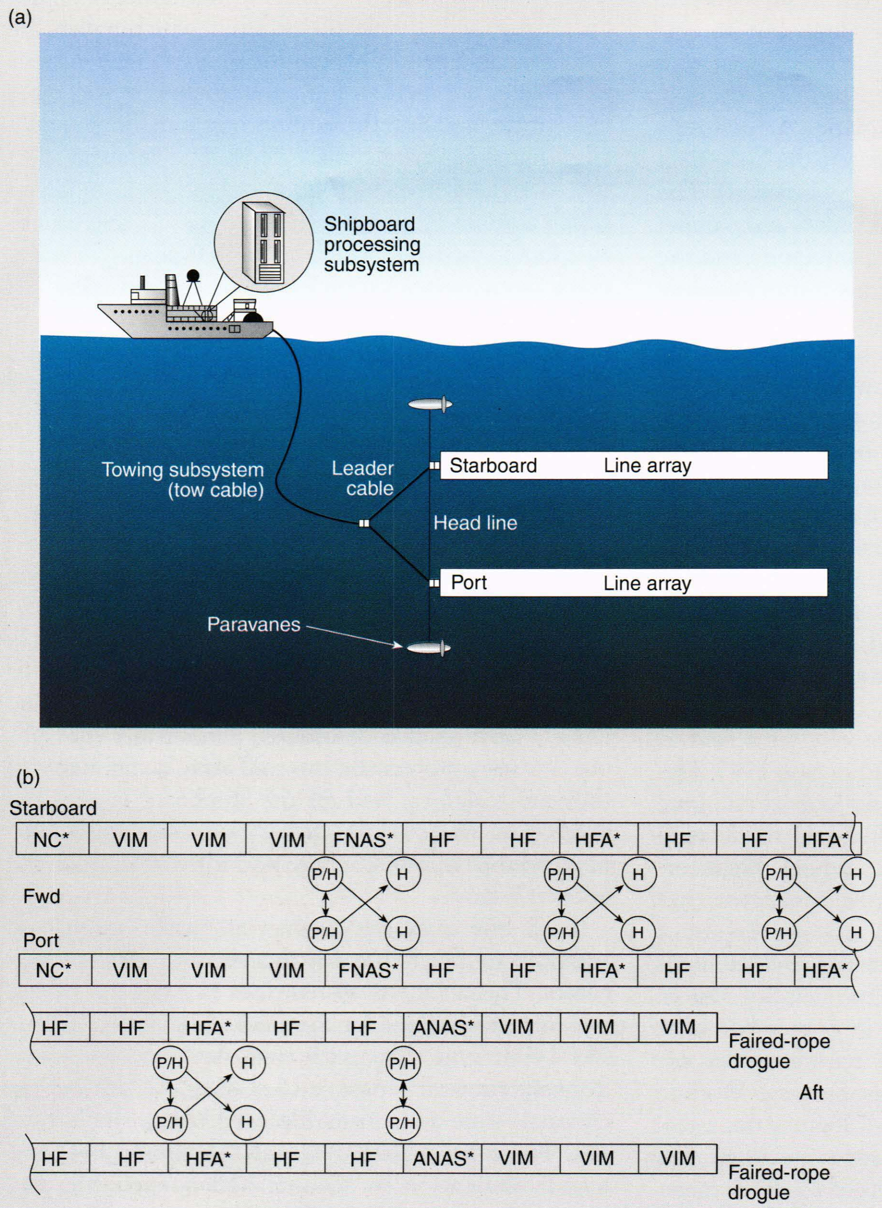

Figure 1. Twinline system hardware. (a) The Twinline consists of two line arrays, a towing subsystem, and a shipboard processing subsystem. (b) Modular line arrays include shape measuring unit pingers and receivers, nonacoustic sensor stations for array shape estimation and correction, and acoustic channels. (NC = nose cone module, VIM = vibration isolation module, FNAS = forward nonacoustic sensor module, HF = high-frequency module, HFA = high-frequency adapter module, ANAS = aft nonacoustic sensor module, P/H = shape measurement unit pinger/hydrophone, H = shape measurement unit hydrophone, NAS = nonacoustic sensor station.)

four adjustable gain stages, perform spectral prewhitening, amplification, infrasonic noise suppression, and antialias filtering. Analog signals from six PGSAs are sent to a single acoustic data transmitter. Each data transmitter contains 14-bit delta–sigma modulator analog-to-digital converters, a digital antialias filter, and circuitry to multiplex six channels of acoustic data onto the data coax.

*Module includes NAS station.

Nonacoustic sensor stations are located at five evenly spaced points throughout the acoustic aperture and at the array–leader cable interface in the nose cone module. Devices in the sensor stations measure pressure, temperature, magnetic heading, pitch, and roll as a basis for shipboard array shape compensation. State-of-the-art small-diameter depth and heading sensors are used with resolutions of ±3 in. and ±0.1°. The sensor stations also supply voltage, current, and array tension information as indicators of array condition and performance.

In addition to array shape compensation in response to heading and depth data, Twinline employs a shape measurement system that acoustically determines line-to-line separation and slip (the longitudinal line displacement) using high-frequency pingers and receivers located throughout the array. The system receives a start ping signal from the shipboard receiver, and all pingers in one line ping together. The signal received by the hydrophones in the other line is then correlated against a stored replica, and time of arrival (equivalent to range) is determined. Since this system operates in the 12- to 30-kHz region, transmission bandwidth is conserved by only transmitting range information to the ship. Accuracy of the system has been measured at ±0.5 in.

The second subsystem, towing hardware, is composed of several electromechanical cable assemblies that provide a mechanical connection to the towship and an electrical path for data, command and control, and power signals. Hydrodynamic bodies called paravanes are also included to maintain the horizontal separation. The towing system consists of six cables and two paravanes. The 3700-ft-long, 1.26-in.-dia. tow cable, which provides an electromechanical connection to the ship, is jacketed and armored and contains several coaxial and single-conductor wires for signal and power transmission. This cable was designed to have extremely low torque (<200 ft-lb at 10,000-lb tension) and rotation (<1°/ft at 10,000-lb tension) to prevent cable torque and rotation from being transmitted to the paravanes and arrays. Leader cables connect the tow cable to each array and provide attachment points for the paravanes and headline. The leader cables are polypropylene-jacketed cables that use a Kevlar strength member. Both the leader cables and tow cable incorporate strum suppression devices to reduce noise from vortex shedding.

Pendant cables are used to attach the paravanes to the leader cables. The paravanes provide an outward force that pulls the line arrays apart and is resisted by the headline. The paravanes are biwing, passive towed vehicles with a cylindrical fuselage and hemispherical nose; vertical stabilizers are mounted on the top and bottom aft end of the fuselage, and horizontal stabilizers are attached to the lower vertical stabilizer. Over the speed range of 2 to 5 kt, the paravanes yield from 44 to 276 lb of lift.[2]

The third component, the shipboard processing subsystem, is made up of 11 equipment racks that supply power to the array, allow operator command and control of array functions, and receive time-division-multiplexed data from the array. Recording, beamforming, and analyzing the received data are additional functions of the processing subsystem.

In all Twinline trials, two parallel signal processing strings are employed: one to measure Twinline performance and one to measure single-line performance. Using parallel processing strings permits direct on-line determination of Twinline performance improvement. In the Twinline string, the telemetry receiver unit (TRU), multisensor interface recorder system, Twinline beam-former (TLBF), and the engineering display station are the key equipment. The TRU, a PC-based unit, serves as the command and control interface to the arrays and performs array power, array synchronization, and data recovery and formatting functions. Interfacing the TRU and TLBF and recording digital tapes for posttrial analysis are the functions of the multisensor interface recorder system. The TLBF, which is implemented in a Sun Work Station using CSPI's supercard array processors, forms full-azimuth, shape-compensated beams by computing a set of weights on the basis of array shape to minimize the total sidelobe power in a specified region outside the mainlobe. The engineering display station provides the acoustic scene (spectrograms and bearing versus time) for the watchstander.

During the 1994 at-sea tests, Twinline's noise gain, backlobe rejection, and reverberation rejection performance were quantified. Results from the tests are discussed in the following sections.

TWINLINE NOISE MEASUREMENTS

Noise gain, an indicator of the Twinline system's ability to detect quiet signals in anisotropic conditions, is the ratio of the beam noise to the average noise on all the individual omnidirectional hydrophones of the array and is a measure of system performance less sensitive to environmental factors. The purpose of measuring the Twinline array's noise gain is to quantify the noise gain improvement that this system offers over a single-line towed array, particularly in near coastal and shallow-water environments. Most of the low-frequency noise in these environments arrives from shipping sources at ranges much greater than the water depth, and consequently with arrival angles near the horizontal. In the beam-former algorithm, the horizontal arrival structure of interfering shipping noise is a primary assumption. The horizontal configuration of the Twinline array, along with the noise assumptions in the beam-former, should optimize the noise rejection capability within small vertical arrival angles of ±20°, with an expected rejection of 20 dB or more. The Twinline's ability to reject noise from the opposite side allows the array to determine the surveillance signal's origin tactically without fear of back-beam noise contamination. For example, in some scenarios the target may be known to be farther toward shore in generally quieter directions, whereas most of the interfering noise arises from commercial shipping lanes or battle group sources farther out in deeper water. In such anisotropic conditions, the Twinline array's ability to reject noise may become particularly useful.

Noise sources arriving at angles near the horizontal have typically thwarted the single-line system's ability to detect quiet targets. A sample of the low-frequency azimuthal noise characteristic of noise from shipping sources is shown in Fig. 2, which can be used to compare the horizontal-beam noise measurements of the Twinline and a corresponding single-line aperture at 90 Hz with a noise field in the Adriatic Sea. The noise field is highly anisotropic, as revealed by the Twinline noise field characterized by several louder individually resolved sources. Azimuthal resolution of horizontal arrays confines these discrete sources to small azimuthal sectors. As a result, quieter directions between the resolved sources are available in which to detect quiet targets. The ability to characterize the quietest azimuths is a critical factor in target detection performance. The left–right ambiguity of the single-line array causes the discrete sources to be reflected about the array's axis (the 0 to 180° line in Fig. 2) in its measurement of the noise field. Thus, for a single-line array, some azimuthal beam directions that would otherwise be quiet are contaminated by noise from the sources in

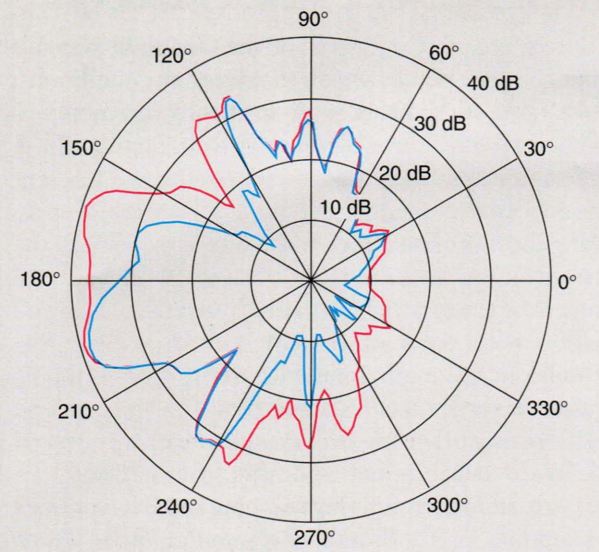

Figure 2. A comparison at 90 Hz in the Adriatic Sea of low-frequency azimuthal noise measurements of the Twinline (blue) with a corresponding single-line aperture (red).

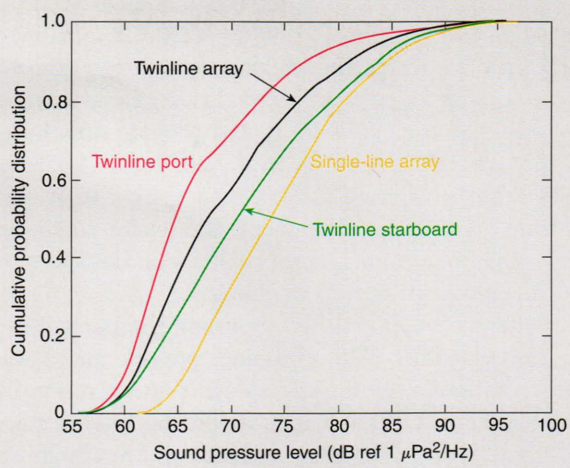

Figure 3. Twinline versus single-line cumulative noise distribution at 55 Hz with subsets for Twinline port and starboard beam distributions.

the conjugate direction. The Twinline array resolves left from right and hence creates more available quiet directions for detection in an anisotropic field. When steered in the direction of a dominant discrete source, the Twinline and single-line arrays will have nearly identical noise levels.

To characterize the performance of the Twinline system, the dynamic nature of shallow-water environments must be taken into account. Discrete noise sources can fluctuate rapidly in level as range changes across the typical shallow-water multipath interference pattern. Moreover, the azimuthal location of the sources will also vary with time as the ships transit. Given the uncertainties in the locations and levels of all the noise sources, a statistical method is the best approach for noise performance characterization. The statistical distributions of noise levels characterize the probability of being below any given noise level and therefore are useful to determine the percentage of times at which detection is possible. Of particular interest to detection performance are the lower tails of the noise distributions, since it is only in the most silent directions that detection of quiet targets can occur. The comparison of single-line noise distribution with Twinline's improved noise distribution makes it possible to predict the long-term expected improvement in noise gain performance.

Figure 3 demonstrates noise gain improvement by juxtaposing the cumulative noise distributions for the Twinline and single-line arrays at 55 Hz in the Adriatic Sea. Separate distributions are also given for the port and starboard subsets of the Twinline beams to put the distributions in context. The entire Twinline noise distribution is about 4 to 5 dB lower than the single-line distribution, showing a long-term advantage of the Twinline system. To illustrate the significance of this gain, consider the probability of detecting a target of received level plus recognition differential at 67 dB. The single-line array has noise below this level only 15% of the time, whereas at 45%, the Twinline has a probability of noise below this level three times more often.

In Fig. 3, the port and starboard noise distributions are significantly different, indicating a general statistical anisotropy in the noise field. If the target direction were known to be confined to the quieter port side, the Twinline array would have about a 7 to 8 dB gain over the single-line system. The Adriatic noise field is anisotropic because much of the commercial shipping traffic is in the lane on the western side of the basin. Surveillance from the basin center for targets toward the east can take advantage of this anisotropy when performed with the Twinline array. The anisotropy is largest in the frequency band around 60 Hz, at the peak of the shipping noise spectrum. For higher frequencies, in the region between 200 and 300 Hz, the anisotropy begins to diminish as the noise becomes more dominated by isotropic wind-wave sources.

For the Twinline array, system noise performance can be ascertained by the distributions of absolute noise levels, but these distributions are specific to one environment. The absolute noise level is primarily determined by the propagation characteristics and shipping density of the environment. Noise gain is a system parameter useful for extrapolating the results from this specific environment to other environments with differing noise conditions. A reasonable prediction of the system performance in other environments can be obtained from noise gain measurements presented here, coupled with historical measurements of omnidirectional noise levels for the other environments of interest.

To produce gain statistics, noise gains for each beam were computed at each individual frequency and time sample. That is, for each time at each frequency, the average hydrophone response was computed. This hydrophone average was then used to normalize the beam noise for all beam directions at that time and frequency. Finally, gain statistics were accumulated across all beams and times for each frequency. Since each sample was individually normalized, the gain distribution is not necessarily the same as the absolute noise level distribution shifted by the omnidirectional noise level. A sample of the resulting noise gain distribution for 55 Hz is shown in Fig. 4. The mean power noise gain is −13.3 dB for this distribution, which is only about 1 dB higher than the corresponding weighted aperture single-line directivity index at this frequency. However, the median gain is −22.5 dB, a markedly higher rejection of noise than is indicated by the mean power. The mean power is dominated by a small number of extremely large values for those beams that are directed at the dominant noise sources. In Twinline testing, most of the beams are significantly quieter. Gain resulting in more than 30 dB of noise rejection, under which extremely quiet sources can be detected, occurs 10% of the time.

Another function of noise gain is the process of separating frequency-dependent environmental effects from system effects. Figure 5 is a summary of statistics from the distributions of noise gain for all frequencies processed. As a general rule, gain increases with frequency as array resolution increases. Analysis of the figure shows that gain is degraded in the vicinity of the half-wavelength line separation (160 Hz in this case). High gain is achieved a meaningful fraction of the time, even for extremely low frequencies. Twinline noise rejection exceeds 25 dB at least 25% of the time for frequencies as low as 40 Hz. The median noise gain is about 25 dB across the entire band from 60 to 135 Hz. The mean power noise gain follows the theoretical gain (smooth curve in Fig. 5) very closely, reflecting the validity of the Twinline array's measurements.

BACKLOBE REJECTION

Single-line arrays have very limited backlobe rejection capabilities. A nominally straight single-line array cannot discern left from right. For a beam steered to an angle of ϕ, the full response beam at conjugate angle $-\phi$ is referred to as the backlobe. Response peaks at angles other than ϕ or $-\phi$ are referred to as sidelobes. For optimal performance, suppressing the backlobe response to typical sidelobe levels is desirable. A perfectly straight single-line array provides no backlobe rejection. The small transverse distortions typical of a towed single-line array can be exploited, and indeed induced, to achieve a small amount of backlobe rejection. Although this distortion is sometimes sufficient to determine which side of the array a signal is on, the distortion is usually not adequate to suppress strong interfering sources.

As discussed earlier, the primary objectives of the Twinline towed array system are (1) to provide instantaneous left–right ambiguity resolution of signals of interest and (2) to reduce backlobe response to −30 dB or more relative to the mainlobe response. Single-line arrays fail to meet these objectives. With the Twinline array, however, both of these objectives are achieved through backlobe rejection. This rejection was initially desired because it was suspected that loud interferers were contaminating many otherwise quiet

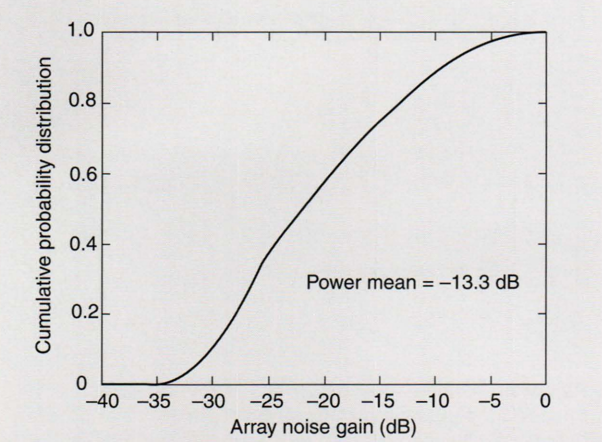

Figure 4. Twinline array noise gain distribution for 55 Hz.

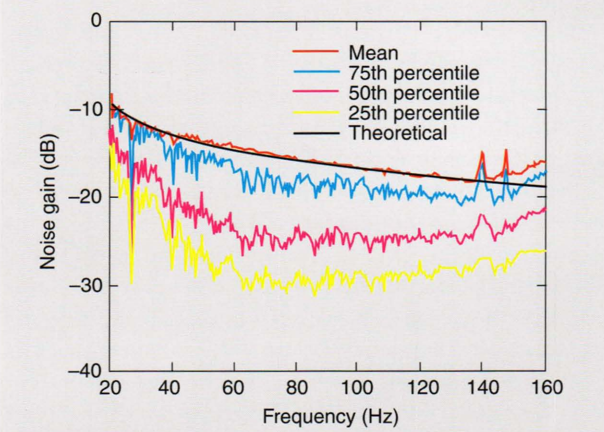

Figure 5. Twinline array noise gain versus frequency graph summarizing noise gain distributions for all frequencies processed.

beams on mirror bearings. In the noise-distribution example in the previous section, the improvement achieved by rejecting this contamination was demonstrated. In addition, the distribution of levels suggests that 20 to 30 dB of backlobe rejection is required to keep the loudest contacts from contaminating the quiet beams.

With a distorted single-line towed array of Twinline's length, it is typically very difficult to achieve much more than 6 dB of backlobe rejection because distortions cannot be sustained. Maneuvers required to attain 6 dB or more of rejection are typically inconsistent with operational requirements as well. In addition, the defocused backlobe response becomes very broad, allowing even more opportunity for shipping noise contamination. Another consequence of rapid changes in the single-line array shape is the reduced capability to measure the array shape accurately and use it in the beam-forming process. The magnitude and period of the required maneuvers also cause significant beam wander. This wander either reduces the signal recognition differential, because the signal does not stay in a beam for long periods of time, or significantly increases the cost and complexity of the display process by requiring the stabilization of rapidly moving beams through a geographic coordinate system.

A horizontal Twinline array eliminates all these single-line problems by providing a stable platform with the horizontal spread of acoustic sensors that is essential for substantial backlobe rejection. The ability of the Twinline shape-adaptive beam-forming algorithm to reduce the backlobe response is a function of line-to-line separation, frequency, main response axis angle, white-noise gain control constraint, and array shape-estimation accuracy. Optimal performance is obtained when the line-to-line phase separation is one-quarter of a wavelength. Under these conditions, both left–right rejection and white noise gain are maximized, and the sensitivity to shape estimation error is minimal.

In less than optimal operating conditions (away from quarter-wavelength line-to-line separation criterion), white-noise gain is reduced and sensitivity to line-to-line shape error is increased; however, satisfactory performance is typically maintained over a wide range of frequencies and main response axis angles. For beams pointed very near forward and aft end-fire, both significant left–right discrimination and satisfactory noise gain performance become impossible to maintain. In these cases, the adaptive weights are tapered to conventional beam-forming (CBF) steering vectors to maintain adequate noise gain at the expense of left–right rejection. The use of CBF steering vectors is not a serious drawback because there is no left–right ambiguity to be resolved at forward and aft end-fire.

Figure 6a is a Twinline bearing-time record (BTR) of the measured noise field during a 180° turn to starboard made in the Adriatic basin in a recent sea test. This 80-min segment of data (time 0 corresponds to the most recent data) represents plane-wave-calibrated levels received on 324 beams, starting at forward end-fire (beam 1) and incrementing clockwise down the starboard side to aft end-fire (beam 162) and back up the port side to forward end-fire again at beam 324. The beams are spaced evenly in cosine space to maintain constant beam crossover gain as a function of azimuth. This method of graphing spaces the beams closer in bearing at and around broadside than near end-fire, where the beams are wider. Red indicates high received levels, and blue denotes levels approximately 30 dB lower.

In the BTR, strong or high-intensity contacts are typically observed as obvious stripes of red or yellow. These contacts move in the opposite direction of the turn. This movement can be seen in a strong red signal as it moves from aft end-fire (beam 162) 80 min back in time, to near broadside (beam 81, time = 40), to near forward end-fire (beam 1, time = 0).

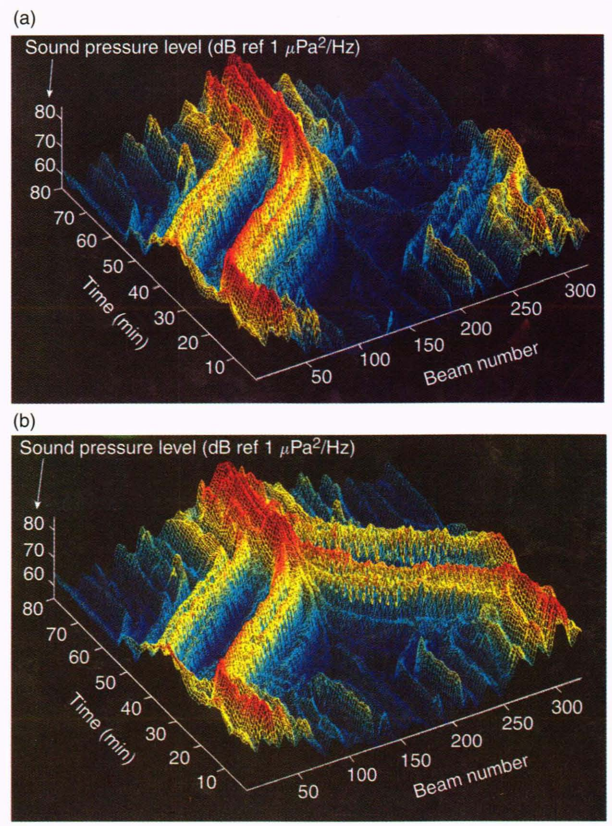

Figure 6. Bearing-time records (BTRs) at 100 Hz during 180° turn to starboard demonstrating the high quality of Twinline left–right ambiguity resolution. (a) Twinline array BTR. (b) Single-line array BTR.

The data set represented in Figs. 6a and 6b was selected for several reasons. First, the very strong broadband source observed at aft end-fire is significant. Measuring backlobe rejection necessitates adequate source levels to make the signals observable and dominant over other sources at the backlobe bearing. In practice, this requirement makes it quite difficult to measure rejection because other ships are often in the backlobe direction. In this particular data set, only a few contacts interfered with the measurement of rejection. Also, the array turn takes this strong broadband source from aft to forward end-fire (roughly from beam 162 to beam 1), making it possible to measure rejection quickly on all beams with a strong source. Finally, the Twinline demonstrated satisfactory operation during a turn with a surveillance array. Consistent functioning during a turn is in itself a noteworthy achievement, given the performance loss in turns characteristic of high-gain systems. Traditionally, high-gain towed systems are 50 to 100 wavelengths long, which at low frequencies makes them very long physically. At normal tow speed (3 to 5 kt) and turn rates (5°/min), so much distortion is typically present in a long single-line array that acoustic performance is severely compromised during and up to 30 min after turns. Since the higher design frequency and resulting shorter length of the Twinline array mean that overall distortion is small at lower frequencies, performance is not appreciably degraded. In addition, the short length results in a more rapid return to a nominally straight configuration after the turn. In the shipping-dominated portion of the spectrum, the Twinline's high noise gain is achieved by backlobe rejection.

Twinline's high gain is particularly impressive given the absence of array shape and separation data and the assumption of a straight and parallel shape during this test. In modeling, the shape-adaptive algorithm has been observed to be extremely sensitive to line-to-line shape estimation errors. Line-to-line separation accuracy to one-twentieth of a wavelength was typically required to achieve adequate backlobe rejection. Therefore, good backlobe rejection is a strong indicator of a very stable array configuration, which is critical to sizing of the beam-former. Adaptive weight calculation is computationally expensive, and a rapidly changing shape would require rapid weight updates.

The backlobe response to the strongest contacts is just visible in Fig. 6a. As the contacts move from beam 162 to beam 1, faint ghost traces of the stronger signals can be seen moving from beam 162 to beam 324 in the opposite direction. These backlobe traces are observed to intersect the weaker contacts that have moved to the port side (beams 162–324) as a result of the turn. At angles away from forward and aft end-fire, the difference between front- and backlobe levels is often 20 dB or more. This finding is consistent with the white noise gain control parameter setting, which was 0.01 for this processing run. This parameter sets the nominal backlobe rejection to 20 dB or greater.

Twinline performance can be contrasted with the single-line array BTR presented in Fig. 6b for the same time period. The contacts in the figure are clearly moving from aft to forward end-fire (beams 162 to 1); however, since the backbeam response is not suppressed, the contacts are also observed to move from beams 162 to 324 at the same strength. At any instant the single-line array cannot resolve left–right ambiguity to determine if a contact is to port or starboard. In addition, the weaker contacts to port (beams 162 to 324) are completely obscured by the energy of the stronger signals to starboard received in the backlobe. In shallow-water testing, left–right ambiguity prevented the single-line array from effectively detecting quieter signals.

A summary of the Twinline backlobe rejection measured during this turn is presented in Fig. 7. Rejection was about 20 dB over a wide range of angles near broadside. This measurement tapers to 5 dB or less near forward and aft end-fire, where blending to conventional beam-forming is performed. The measurable backlobe rejection depends significantly on the noise field. When the loud source is between 110 and 120° relative bearing (beam numbers 250 to 260), the apparent rejection is reduced because at this time interfering contacts happen to be in the backlobe direction, making any measurement impossible. In these cases, shipping unavoidably causes the rejection ratio measurement to be noise limited.

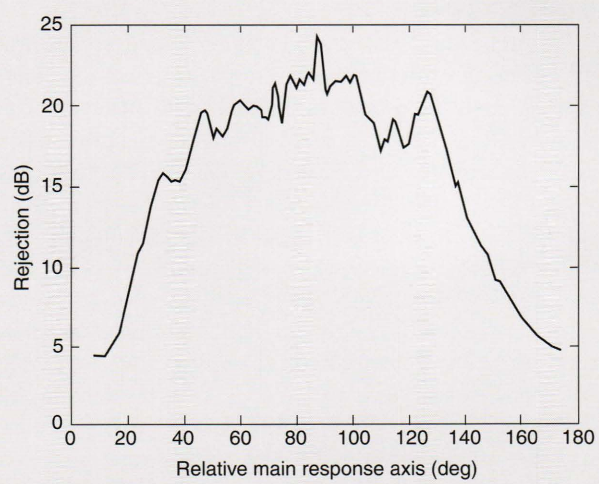

Figure 7. Twinline backlobe rejection during a 180° turn to starboard.

REVERBERATION REJECTION

In addition to its aforementioned advantages in passive surveillance, Twinline is expected to improve active surveillance by reducing the masking effect of backbeam reverberation. Active systems detect and track targets by transmitting known signals through the ocean and listening for their echoes. Target returns are usually weak compared with the many sources of interference, including shipping noise, spurious returns of the transmitted signal from nontarget scatterers, and reverberation. In many environments, particularly shallow-water littoral regions, reverberation is the dominant interference mechanism. By steering a null to the back beam, Twinline has the potential to detect weak mainlobe target signals that would normally be obscured by strong backlobe reverberation.

Low-frequency broadband data collected off the coast of New Jersey during the first Twinline engineering trial in July 1994 demonstrated the system's reverberation rejection capability and offered a brief indication of its potential in active surveillance. Explosive sources have an identifiable energy spectrum with peaks around multiples of a fundamental bubble-pulse frequency. The tow ship followed a northeast heading roughly parallel to the bathymetric contours. Received energy was resolved in azimuth using the Twinline null-steering beam-former and converted to time series by inverse Fourier transform. Nonideal tow conditions during the data collection caused a half-degree skew between the two lines that was accounted for by the shape-compensated null steerer. Though environmental conditions surrounding the tow area create distortions that could negatively affect Twinline performance, the recently updated SMU pinger system will improve future operation by providing enough information to calculate a relatively accurate estimate of the line-to-line shape.

Figures 8a and 8b show beam power level versus time following the first arrival of energy from an explosive source. Azimuth is measured clockwise from the tow ship heading. The data were filtered to include energy around the third and fourth bubble-pulse harmonics. Five distinct arrivals are evident in Fig. 8a near broadside (90°). The first of these, the direct blast, defines the time origin and represents waterborne energy carried along a direct path between the detonation point (approximately 5 nmi from the Twinline) and the receiver. The direct blast is resolved clearly to the starboard side at 95°, with 20 dB of rejection on the conjugate bearing (265°). Subsequent arrivals correspond to propagation paths with increasing numbers of boundary interactions and, as a result, increasing vertical arrival angles. Because the apparent separation between the two arrays decreases as vertical arrival angle increases, ambiguity resolution degrades with each successive arrival. Diffuse out-of-plane energy scattered from the sea floor is observed between arrivals. The curved patterns approaching end-fire (0, 180, and 360°) after the first bottom-bounce arrival correspond to the increasing distance between the bottom reflection point and the receiver. Reverberant energy begins to resolve to one side or the other beyond the third arrival. The curved patterns appearing after 20 s may have been produced by ridges or undulations associated with the Hudson Canyon, which runs roughly perpendicular to the array's heading.

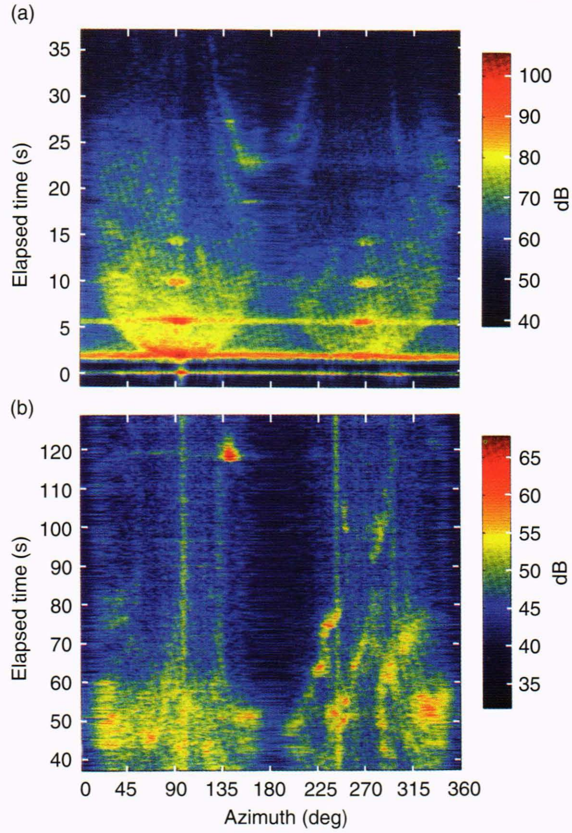

Figure 8. Unambiguous reverberation and noise fields following an explosive-source direct blast. (a) Direct arrival resolves to starboard with 20 dB of rejection on port side. (b) Discrete reverberators are resolved. A strong distant reverberator at 120 s resolves to starboard with 20 dB of rejection on conjugate bearing. Four (continuous) shipping noise sources are resolved.

Several discrete features are resolved unambiguously in Fig. 8b. Distinct reverberators span the port azimuths (180 to 360°) in the upslope direction between 40 and 100 s after the direct blast, implying bottom ranges between 16 and 40 nmi. A particularly strong reverberator, more than 20 dB above ambient noise, resolves to the starboard side near 140° approximately 2 min after the direct blast. Although a single-line array would show a mirror image on the conjugate bearing (220°), Twinline rejects this feature by 20–25 dB. The elapsed time suggests reverberation from a bottom feature about 45 nmi from the Twinline receiver. In addition to resolving discrete bottom features, Twinline unambiguously resolves four continuous shipping noise sources represented by narrow vertical bands of energy in Fig. 8b.

Figures 9a and 9b show the distribution of power versus dimensionless frequency (frequency divided by array design frequency) at the arrival times of the direct blast and the strong distant feature of Fig. 8b, respectively. Both arrivals display spectral peaks around the source's third, fourth, and fifth bubble-pulse harmonics (dimensionless frequencies 0.42, 0.56, and 0.70), verifying that the distant signal is indeed a reverberation return. The high energy of the direct blast (95° in Fig. 9a) poses a stringent test of Twinline's backlobe nulling capability. Nonetheless, 25 to 30 dB of backlobe rejection is attained on the conjugate bearing (265°) across the entire frequency band. The distant feature arrival (140° in Fig. 9b) is suppressed on its conjugate bearing (220°) by more than 20 dB. The examples illustrate that Twinline backlobe nulling is effective across a large portion of the system's frequency band.

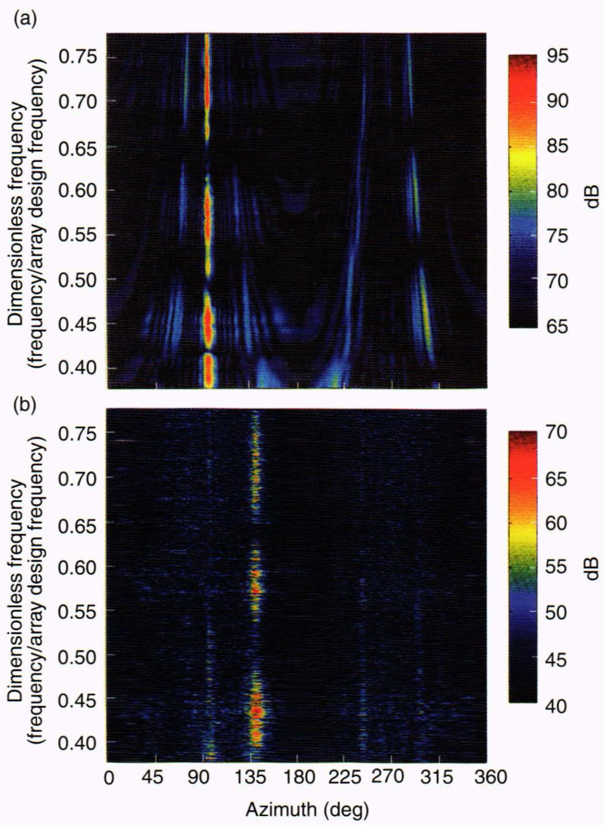

Figure 9. Power spectra of (a) direct blast and (b) distant reverberation arrivals, each showing 20 dB of left–right rejection across three bubble-pulse harmonics.

SUMMARY

The noise statistics discussed in this article show that the Twinline array achieves extremely high gain against shallow-water ocean noise for large percentages of time, providing excellent opportunities for quiet target detection.

Initial testing of the Twinline array and shape-adaptive beam-former was successful and demonstrated a substantial improvement over the single-line array. The Twinline array effectively resolves left–right ambiguity and rejects shipping noise and other contaminants through backlobe rejection. Median backlobe rejection of +20 dB was measured over a wide range of frequencies and angles for many hours of sea-test data. Backlobe rejection up to 37 dB was obtained on one particular run, giving an indication of the Twinline system's ultimate performance potential. In measuring, it was assumed that the array lines were straight and parallel with a constant amount of longitudinal slip between them. Considering that precise estimates of the Twinline array's line shape and separation were not available, the level of performance achieved is significant, suggesting a parallel and very stable towing configuration of the two lines. The stable configuration observed signifies that rapid update of the beam-former weights is not required, which in turn reduces the computational load requirements of the beam-former.

Results of explosive-source measurements demonstrate Twinline's reverberation-rejection capability. Backlobe direct-blast energy and distant bottom reverberation were suppressed across a broad low-frequency band with left–right rejection of more than 20 dB despite nonideal towing conditions. The findings indicate potential for detecting weak target signals that might otherwise be obscured by ambiguous beam reverberation in single-line surveillance systems. An active test planned for fall 1995 will further quantify Twinline's reverberation suppression capabilities.

The Twinline array testing demonstrated the improved performance that towing a horizontal aperture can provide in shallow water environments. In 1995, Twinline's active and passive performance will be assessed further during Fleet exercises.

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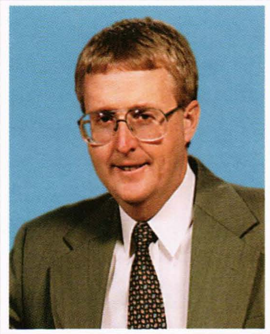

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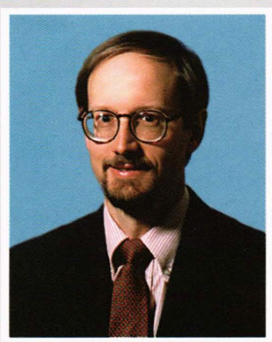

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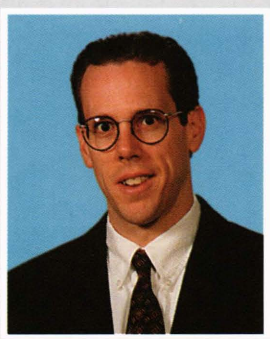

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