JOSEPH S. LOMBARDO, BRUCE K. NEWHALL, and JEAN-PIERRE FEUILLET

NEW ARRAY TECHNOLOGIES FOR TARGET DISCRIMINATION

New mobile acoustic sensor arrays are being developed to address the changing requirements for submarine surveillance. Recent measurements from a new experimental towed array 3.5 nmi long determined that the deep ocean will support coherent acoustic propagation at very low frequencies. Thus, an aperture of that length could be used effectively for open-ocean surveillance, but its performance can be severely limited by operational and water depth constraints in littoral environments. A higher-frequency twin-line array is being developed to achieve higher gains in coastal regions with reduced horizontal signal coherence and additionally to resolve the left–right ambiguity inherent in single-line arrays.

INTRODUCTION

The challenges facing undersea surveillance have multiplied in this era of the "new world order." The Commonwealth of Independent States continues to push forward the state of the art in submarine design, making their new nuclear-powered submarines some of the most capable undersea weapons in the world. These submarines are able to submerge after leaving port and remain hidden throughout a mission. Their nuclear-powered vessels can cripple naval forces and maritime shipping in all regions of the globe. Cruise-missile–equipped submarines can launch air strikes from coastal waters, and ballistic-missile–equipped submarines can launch a nuclear attack without straying far from home port. Technological advances have made these platforms faster, quieter, and harder to detect. As long as these weapons remain operationally ready and in the hands of potentially unstable governments, the U.S. Navy must be able to find and destroy them.

The emerging military powers of the world have long recognized the destructive ability of the mobile and hidden undersea weapon. Many countries now construct and export diesel/electric-powered submarines, and these submarines are in the naval inventories of many potential adversaries. But such submarines must transit long distances on the surface and then submerge to attack blue-water maritime forces. When submerged and operating on battery, they are quiet and hard to detect acoustically, but, because of their vulnerability on the surface, diesel/electric submarines are expected to operate in coastal waters where they can defend against maritime forces approaching the shores. In many coastal regions the water depths impede the long-range propagation of highly coherent acoustic energy. New strategies must be developed to maintain surveillance over these platforms when they operate in their home waters.

We will discuss the development of two new sensors to support these strategies. The first is designated Surveillance Towed Array Sensor System (SURTASS) 3X because it is about three times the length of the production SURTASS array. This experimental array is used to resolve the issues associated with the development and application of very-low-frequency higher-gain arrays operating against advanced nuclear submarines in open-ocean environments. It has been deployed with success in both the Pacific Ocean and Mediterranean Sea. Results obtained from the Pacific, but typical of both areas, are presented. The second sensor, designated SURTASS Twinline, consists of two identical arrays towed side by side. The Twinline is being developed for deployment in littoral waters to operate against the diesel/electric target. Further rationale for the design of this sensor system is also presented. The initial deployment is scheduled for spring 1994.

OPEN-OCEAN ADVANCED SENSOR

The most successful sensors used for long-range open-ocean surveillance exploit the detection of acoustic energy radiated from the submarine. The origins of the energy are the propeller-blade rotation, resonances within the hull, and the noise generated by the machinery within the vessel.

The propagation of acoustic energy in the oceans is influenced by variations of the temperature, pressure, and salinity with depth; by the depth of the water column; and by the composition of the ocean bottom. The combination of these conditions is used to determine a sound-speed profile and the acoustic propagation characteristics. A typical profile of deep-water open-ocean sound speed is shown in Figure 1. The sound speed in the upper layers is influenced by seasonal variations in the surface temperature and by the wave action mixing the surface water

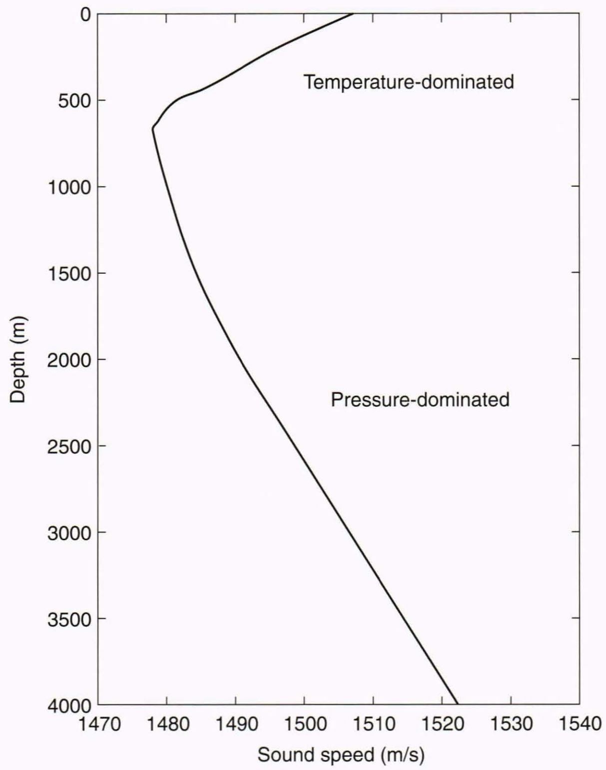

Figure 1. Variation of sound speed with depth for a North Pacific site in June. (Reprinted, with permission, from Ref. 1, p. 243. Copyright © 1984 by John Wiley & Sons, Inc.)

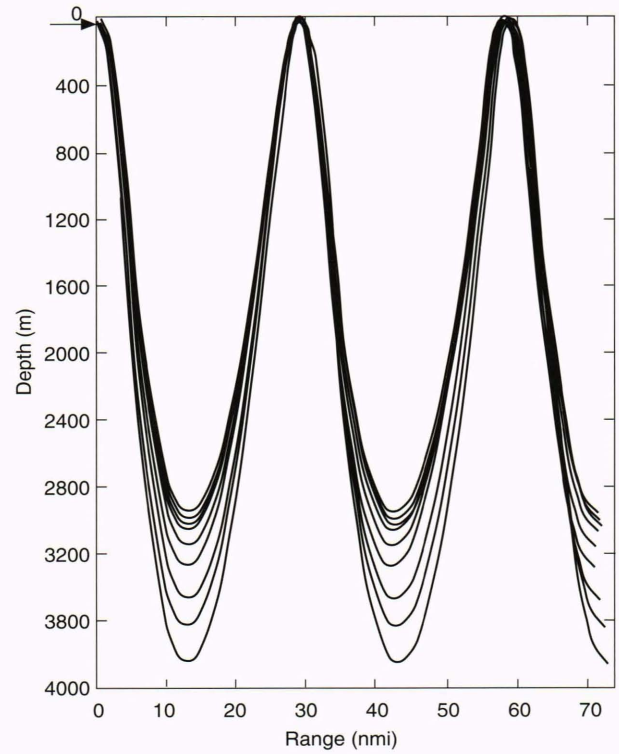

Figure 2. An acoustic ray trace for the North Pacific profile shown in Figure 1 for a source depth of 25 m. Convergence zones are formed near the surface with a spacing of about 30 nmi. Arrow points to source. (Reprinted, with permission, from Ref. 1, p. 245. Copyright © 1984 by John Wiley & Sons, Inc.)

down to lower depths. As depth increases, temperature decreases, producing a negative gradient in the sound speed. At an ocean depth where the temperature no longer decreases, the increasing pressure causes the sound velocity to increase.

Rays of acoustic energy radiated spherically from an object in a layer of decreasing sound velocity will be refracted downward. When the energy reaches a depth where the sound velocity increases, it will turn around and be refracted upward. The energy from the multiple rays is refocused in regions called convergence zones, as shown in Figure 2. These zones are regions of high-intensity sound focusing associated with caustics in the ray solution to the wave equation.[1] Convergence zones form concentric rings around a horizontally isotropic source with a separation of about 25 to 35 nmi, depending primarily on the sound-speed profile. Within the convergence zones the acoustic energy exhibits both higher levels and large spatial coherence. Long-range open-ocean mobile acoustic sensors are designed for optimum detection performance in these zones.

TOWED ARRAY BEAM-FORMING CHARACTERISTICS

A linear array of sensors can have an increased signal-to-noise gain relative to a single sensor. The signal gain is achieved by coherently summing the phased sensor outputs across the entire array. The phasing is calculated to compensate for the phase delays from a given arrival direction. When the array is properly steered to match the direction of the arriving signal, all the sensor signal outputs will add coherently in phase, producing an increased signal response. Interfering noises arriving from other directions will not be properly phased and will tend to partially cancel, producing a weaker response. The beam pattern of the array describes the array response as a function of the direction of the interferer for a given signal steering direction. The response peaks near the steering direction; this phenomenon is known as the array mainlobe. The lower responses to noise outside the mainlobe region are called sidelobes. Figure 3 shows a sample beam pattern for a line array steered broadside at 90°. The width of the mainlobe is a function of the length of the array relative to the wavelength of sound. Very-low-frequency sounds with very long wavelengths require an extremely long array to produce a narrow-mainlobe high-resolution response.

At very low frequencies in the ocean, much of the noise interference arises from merchant ships. These discrete loud sources will mask a target signal if both the target and interferer reside within the same mainlobe. A high-resolution array with an extremely narrow mainlobe response is more likely to be able to separate the target from all of the interfering merchant ships. When the target is isolated from the interferers, the interference noise will be reduced by the sidelobe response of the array. Sufficiently loud interferers may still mask quiet targets if the sidelobe response is not sufficiently low. Thus, detection

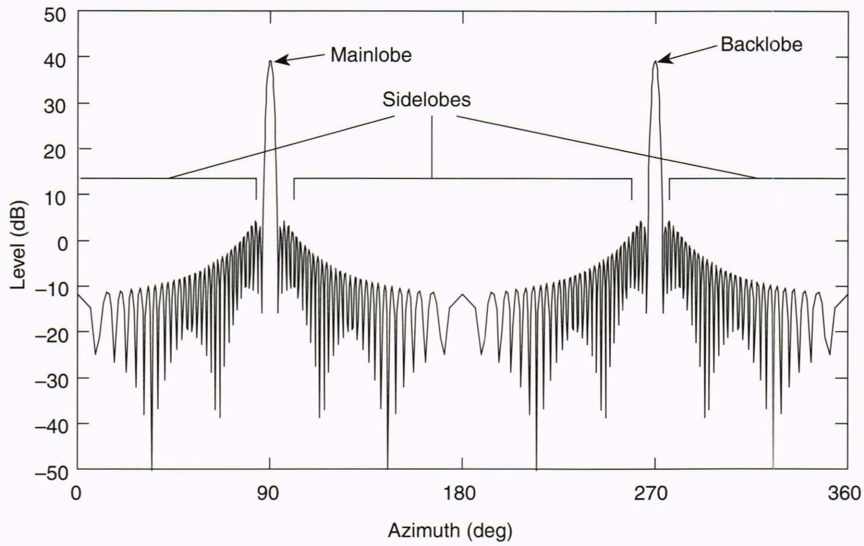

Figure 3. The beam pattern of a horizontal line array steered for a broadside mainlobe at 90°, showing backlobe ambiguity at 270° and sidelobe responses for signals from other directions.

of quiet targets in the ocean requires both high resolution and low sidelobe response.

An experimental large-aperture towed array was constructed to determine the limits of achievable array gain and resolution for very low frequencies in an open-ocean environment. This SURTASS 3X array was assembled using three SURTASS low-frequency apertures connected in series. Hydrophone sensor elements were summed to produce a 100-wavelength aperture at very low frequencies. Special attention was given to obtaining an array with precise element-to-element matching in amplitude and phase outputs to produce low sidelobes. Additional care was taken to ensure that all 200 elements operated properly. Elastic energy-absorbing sections were located at the forward and aft ends of the array to isolate it from mechanical noise generated by the tow ship and from hydrodynamic turbulence at the end of the string. The combined length of the acoustic aperture and elastic sections was about 3.5 nmi. Twelve array-heading and depth sensors were spaced along the array with tension and temperature sensors located at each end.

Extremely long arrays do not follow the tow ship in a perfectly straight line. To measure and compensate for the deformations in the array caused by the tow ship motion, twenty-four high-frequency equally spaced detectors were placed across the aperture. They were used to measure the arrival time of a short-duration signal from a source towed broadside to the aperture. The arrival times were used to measure the geometry of the elements in the array; this information is required for proper signal phasing.

The SURTASS 3X was deployed in the Pacific Ocean early in the spring of 1991 in an experiment designed to determine the limits on array performance imposed by the open-ocean medium. The objectives of the test were to determine if a well-maintained, highly directive array with shape compensation could discriminate between individual ships and find quiet ocean regions between the ships where enhanced detection of submarines could occur. The excellent sidelobe performance of the array system permitted the quiet directions to be observed without contamination from loud sources in other directions. Peak sidelobe levels were measured at 42 dB below the peak of the maximum response of the mainlobe; average sidelobes were about 47 dB below the peak response. For comparison, current fleet arrays have average sidelobe levels about 25 dB below the peak response. This outstanding result is attributed to the absence of element outages and the close amplitude and phase matching of the element outputs.

For highly directive arrays to achieve their full potential, the received signal must possess coherence across the receiver aperture. Measurements of the coherence shown in Figures 4 and 5 were made on known signals transmitted from a projector ship as it increased in range from the array tow ship. At that time the projector was transmitting a continuous-wave tone at a frequency near the design frequency of the array. For the measurements in Figure 4, the projector was at a range of 116 nmi, placing it in the fourth convergence zone. Figure 4A presents a matrix display of the coherence between all pairs of elements in the array. The main diagonal (i.e., the line from the upper left of the plot to the lower right) represents each element's coherence with itself and is always unity. Figure 4B is a horizontal cut through the matrix showing the dependence of the coherence on element separation. For this example, the coherence amplitude is given for combinations of an element near the end of the array with every other element. The figure shows that for an acoustic aperture 3 nmi in length, the coherence of a signal originating at a range of over 100 nmi is almost completely preserved. This result demonstrates that very-high-gain arrays can effectively operate in the open ocean.

High coherence is not always maintained at ranges where the array is not totally within the convergence zone. Shorter coherence lengths are produced whenever significant environmental variations disturb the propagation across the aperture or when multiple propagation paths produce interference patterns across the aperture.

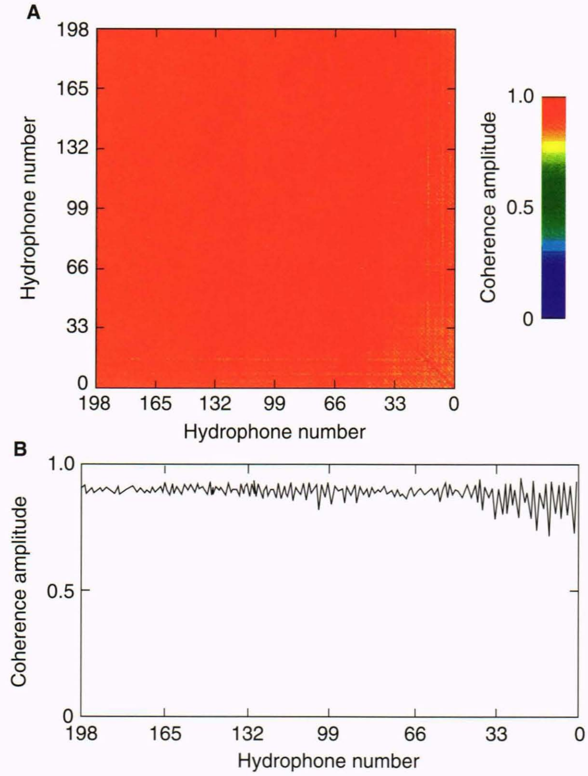

Figure 4. The magnitude of coherence measured across the 3x array from a signal located in a convergence zone at 116 nmi. The ocean supports nearly complete coherence across the full aperture length in this example. **A.** Coherence matrix displayed over all hydrophone pairs. **B.** Coherence as a function of hydrophone separation from an element near the end of the array.

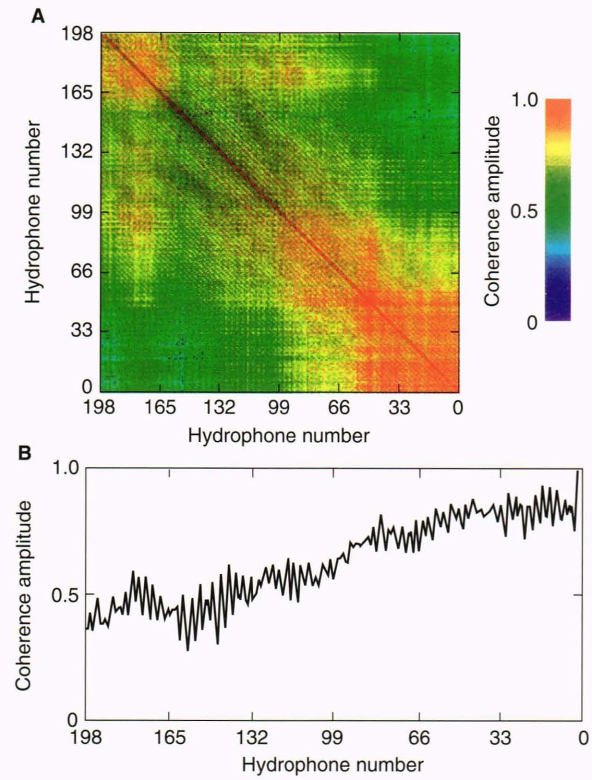

Figure 5. The magnitude of coherence measured across the 3x array from a signal between convergence zones at 140 nmi. Degraded coherence compared with Figure 4 can result from multipath interference between zones. **A.** Coherence matrix over all hydrophone pairs. **B.** Coherence as a function of hydrophone separation.

Figure 5 presents results obtained when the projector ship was approaching the fifth convergence zone. The coherence matrix indicates that high signal coherence was maintained only over portions of the string at this range.

DIRECTIONAL NOISE FIELDS

The extent to which an array can resolve the individual coherent sources that interfere to form the noise field greatly influences the performance of the array system. Reconstructions of the instantaneous noise field have been made. A perfectly straight line-array responds equally to signals arriving from conjugate directions on the left and right sides of the array. Granata[2] developed a technique for resolving this left-right ambiguity of the array by using the known distorted position of the elements. Figure 6 presents an example of the result of applying this technique when a tow-ship turn produced a large bow in the array. The figure gives the beam output of the array as a function of bearing. Individual spikes represent individual ships; the broad spatial signal areas are caused by multiple ships in several adjacent beams or by array bearings with lower spatial resolution (i.e., the end-fire beam 90° from broadside to the array). The site of the measurement is southeast of Hawaii in an area of low local shipping density. Considerable shipping is present both to the northwest of this site around the islands and to the north and east traveling along the North Pacific trade routes to the West Coast of the United States and to the Panama Canal. Much less shipping occurs to the east off South America and to the south and southwest in the South Pacific. The figure shows that from a measurement site with sparse nearby shipping, a high-resolution array produces many quiet beams that can be used to exploit quiet signals.

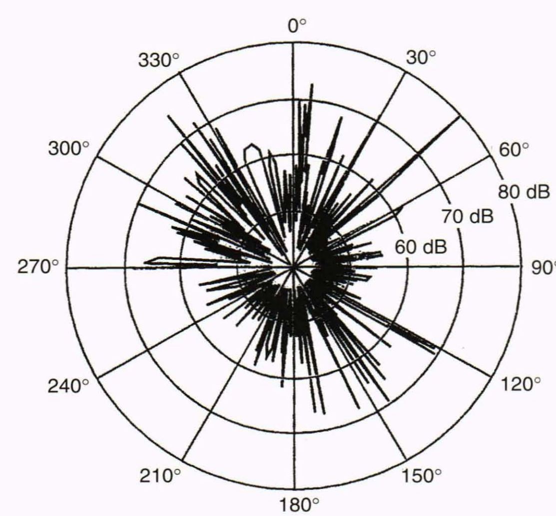

Figure 6. Instantaneous azimuthal acoustic noise field, displaying numerous resolved shipping sources. The field was deduced from the left-right resolution provided by array-shape-compensated data measured when the 3x array was deformed in a turn.

Results from the 3X experiment demonstrate that the open-ocean environment supports the use of large-aperture high-gain systems. The same sensor may not perform as well in shallow-water littoral environments, however. Acoustically shallow regions exist where the water depth is not great enough for the energy to be refracted upward and converge. In those regions the energy interacts with the bottom. The interaction can be a reflection, an absorption plus a refraction in the bottom followed by a reentry into the water column, or conversion into other types of bottom-propagating waves. The acoustic energy interacts with irregularities in the sediments and the underlying rocky basement to destroy the horizontal coherence of the signal. In addition, some coastal areas are not deep enough to support propagation of very-long-wavelength very-low-frequency sounds. Optimum propagation frequencies in shallow water are higher than in the open ocean. A more complete description of shallow-water propagation is given by Boyles and Biondo (Ref. 3 and their article in this issue).

MULTILINE ARRAYS

The 3X array provided high gain in the open ocean and even performed successfully in the deeper shallow-water areas along the edges of the continental shelf in a recent test in the Mediterranean. Very-low-frequency long-aperture performance is greatly reduced, however, in most continental shelf areas. First, the long aperture is unwieldy for safe towing in shallow water because part of the array may drag on the bottom or float to the surface. Second, the very low frequencies do not propagate well in most shallow-water areas. Finally, since the horizontal coherence lengths are shorter in shallow-water environments, increased array gain cannot be achieved with longer apertures.

An alternative to a linear aperture is a planar aperture. A planar aperture or array can be achieved by towing two or more linear arrays side by side. For our initial evaluation, a twin-line system using two identical acoustic apertures was developed. The apertures are spaced so that the element output phases can be adjusted to sum the energy arriving from one side of the array while canceling the energy coming from the conjugate direction on the opposite side of the array. The twin-line array can thus eliminate the left-right ambiguity of the single-line array and produce increased gain without requiring increased coherence lengths.

Responses of the twin-line array have been predicted for a variety of array configurations and beam-forming steering techniques.[4-6] Figure 7 shows the azimuthal response of a twin-line array with a conventional beam-forming process. The conventional beam former phases all the elements to match perfectly the arrival phase for the given mainlobe steering direction (90° or broadside to the array) as shown in the figure. This phasing produces a strong response in the mainlobe direction and low sidelobes in all other directions, except for the backlobe direction (270° in Fig. 7). For a single line, the backlobe response is equal to that of the mainlobe (Fig. 3), but for the twin line, the backlobe shows some degree of suppression. Signals from the right side of the array will

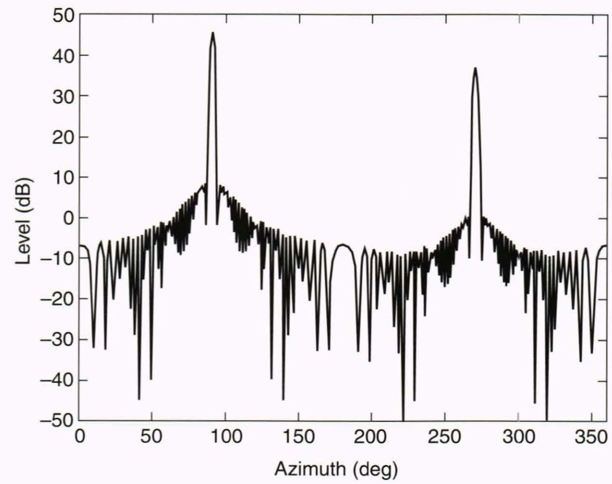

Figure 7. Twin-line-array beam pattern generated by a conventional beam-forming technique. The backlobe ambiguity is reduced.

intercept the right line earlier than the left line, whereas signals from the left-side backlobe direction intercept the left line first. This difference in arrival times between the two lines produces different phases that can be used to discriminate left from right arrivals. If the two lines are phased for a mainlobe arrival from the right side, the backlobe will generally be partially out of phase and show some degree of suppression, as in Figure 7. The amount of backlobe suppression depends on the frequency and steering direction; the maximum backlobe suppression for broadside mainlobe steering occurs at the frequency for which the line separation is one-quarter wavelength. With this maximum suppression, a perfect null is formed in the back-beam direction, producing complete left-right resolution. This outcome suggests that better twin-line performance can be achieved by adjusting the phases between the two lines to steer a null to the back beam rather than by steering the peak to the mainlobe. Figure 8 shows the response of such a null-steering beam former for the same situation presented in Figure 7. When the line phases are steered to produce a backlobe null, they may not produce perfect mainlobe phasing. Imperfect phasing will suppress the mainlobe response. The null steering has a slightly reduced mainlobe response in Figure 8, but has low sidelobes everywhere outside the mainlobe. The null steering results in increased array gain because it eliminates noise contamination of the mainlobe target by interferers in the back beam.

The null steering will produce good performance whenever the mainlobe does not suffer too much suppression. Figure 9 maps the mainlobe response as a function of dimensionless frequency and steering azimuth. The dimensionless frequency is the ratio of frequency to the array's design frequency. The red and orange areas correspond to high mainlobe responses and good performance by the null steerer. Good performance can be achieved over a large region in frequency-azimuth space. The yellow, green, and blue areas represent regions of increasing mainlobe suppression and poorer performance

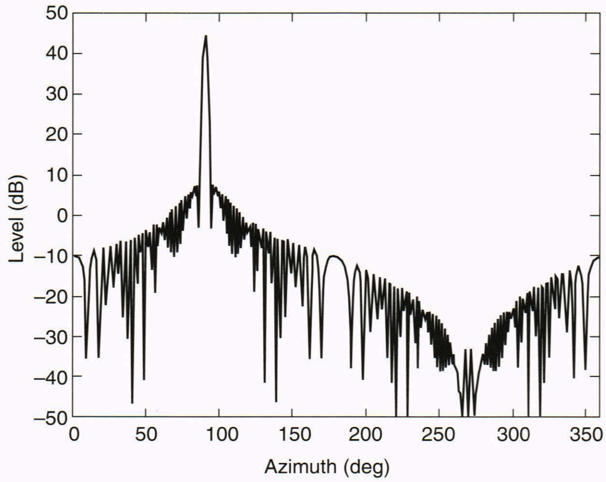

Figure 8. Twin-line-array beam pattern generated by a null-steering beam-forming technique. The backlobe ambiguity is eliminated.

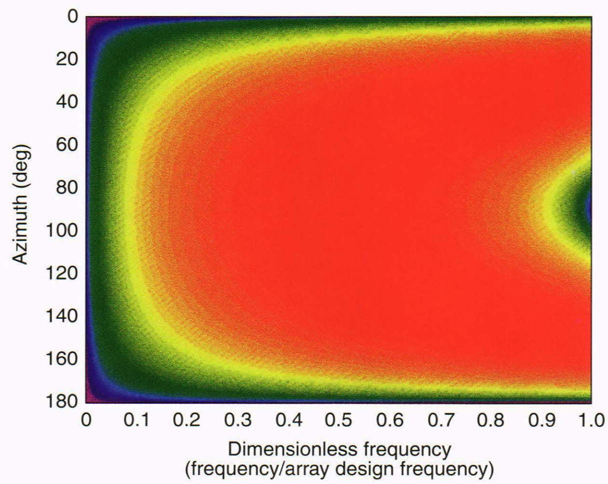

Figure 9. The mainlobe response of the twin-line array when the backlobe is nulled. The lines are separated by a distance equal to one-half wavelength at the array's design frequency. Null steering is an effective technique over a wide range of azimuths and frequencies, as shown by the red and orange regions. Null-steering performance is progressively degraded in the yellow through blue regions, as the mainlobe is suppressed along with the backlobe.

by the null steerer. In Figure 9, the lines are assumed to be separated by the same amount as the separation between the elements within each line, namely one-half wavelength at the array's design frequency. The null steerer achieves poor performance at the very lowest frequencies because the line separation is small compared with a wavelength. The small separation makes the null very wide so that all directions are nulled, including the mainlobe. Performance is poor extremely close to end-fire (0° and 180° azimuth) because the near-end-fire back beams are extremely close to the main beam. In this example, the null is sufficiently wide to suppress the main beam when the null is steered to the back beam. Finally, the one remaining region of poor performance is near broadside at the design frequency. The poor performance occurs when one line is a full cycle out of phase with the other. When the desired null is steered to the backlobe, the one-cycle ambiguity also superimposes a null in the mainlobe direction. Outside these limited regions, good performance should be achievable.

Figure 10 is a diagram of the towing configuration used in the SURTASS Twinline project. To facilitate the deployment of two line arrays from a single tow ship, a Y cable is used. The separation between the array lines is determined by the use of dual paravanes and a header line between the arrays, as shown, and is changed by increasing or decreasing the length of the header line before deployment. The separating force created by the paravanes is sufficient for a large range of header line lengths and resulting array separations.

The paravanes and header line can control only the positions of the head of the line arrays with respect to each other. Hydrodynamic forces from currents and tow-ship maneuvers may cause the array lines to deviate from perfectly parallel lines. Since the relative positions of all the array elements in both apertures must be known to achieve the required array performance, an element-locating system is being installed in the array lines. The system consists of a series of projectors that transmit short tone bursts and a series of high-frequency detectors across from the projectors to make timing and geometry measurements. The projectors operate in excess of six octaves above the design frequency of the array lines to avoid any noise contamination into the acoustic data frequencies. This element location concept is also shown in Figure 10. Projectors on the port array transmit to receiver/detectors in the starboard array. Redundant measurements are made with the starboard projectors transmitting to receiver/detectors located in the port array. The arrival times are converted into separation distances using the measured ocean sound speed. These separation measurements give the relative locations of the elements with respect to each other but do not give the orientation of the two arrays relative to a fixed coordinate axis. The orientation is obtained from the precision heading sensors located at intervals along each array.

CONCLUSION

New acoustic sensors are being developed to address the detection and tracking of advanced nuclear submarines operating in the open ocean and quiet diesel submarines operating in littoral waters. An experimental large-aperture very-low-frequency array was built to investigate the ability of the ocean medium to support the generation of narrow beams that could look between ships into low-noise regions. Measurements indicate that the ocean preserves the spatial coherence of acoustic energy and that arrays can be operated to form narrow beams that resolve individual ships. A twin-line higher-frequency array is being developed to optimize array performance in shallow water. The sensor will increase array signal gain by adding more sensors without requiring more spatial coherence. The sensor will reduce the array noise gain by nulling energy entering the aperture from the array's ambiguous side. Tests planned for summer 1994 will quantify the performance of this sensor.

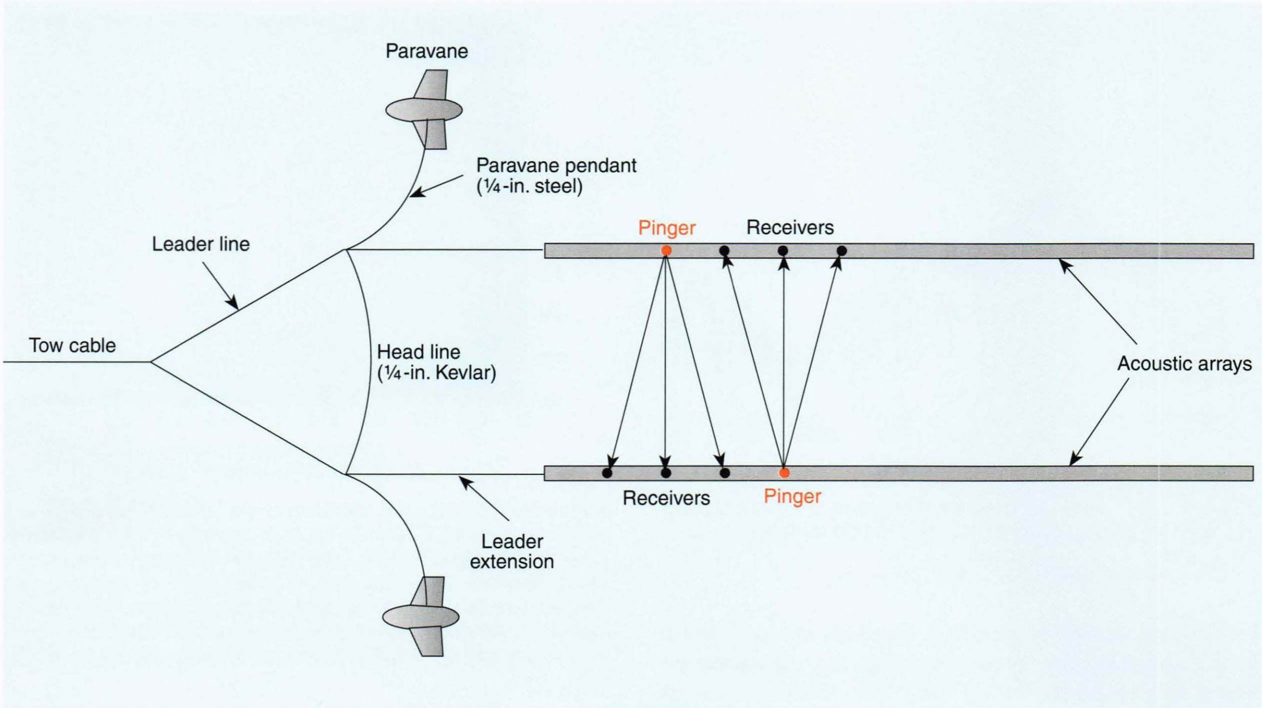

Figure 10. Top view of the twin-line array and towing configuration. Paravanes produce a separation force to maintain the line spacing at the head of the arrays when towing. An intraline projector system provides accurate measurements of the line separation along the entire length of the arrays. (Figure not to scale.)

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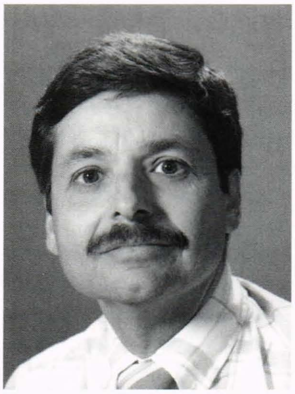
THE AUTHORS



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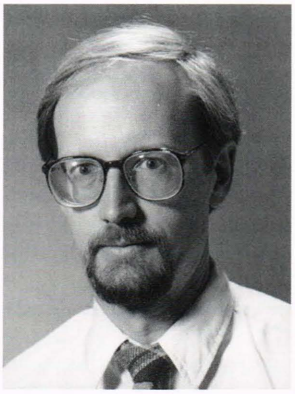

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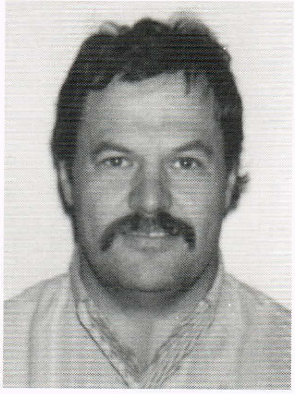

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