Buoyant Cable Antenna Technology for Enhancing Submarine Communications at Speed and Depth

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Future military and naval operations will require substantially increased connectivity and communications for force coordination, mission planning, and tactical execution. The submarine force is seeking to achieve these goals while preserving its important attributes of stealth and survivability. The Defense Advanced Research Projects Agency (DARPA) has initiated a program in conjunction with the Navy to examine advanced antenna array technologies to address these needs. This article describes the DARPA approach and APL's role in the program. (Keywords: Antenna, Communications, Submarine.)

INTRODUCTION

Dramatic changes are occurring in the strategies and methodologies of future U.S. military operations, as recently described in Joint Vision 2010.[1] The major thrust of JV2010 is the integration of forces to achieve full-spectrum dominance in undersea, air, and land warfare. A key Navy element of these changes is the concept of "network-centric" warfare, as defined by IT-21,[2] whereby all major platforms and military units will be interconnected at the command, tactical, and in some cases weapons employment level to provide this coordination of forces. To achieve such a level of integration and interconnection, all platforms will require enhanced capabilities to receive and transmit information at varying rates and latencies from satellites and other platforms.

Today, submarines must frequently operate at periscope depth to maintain ready and effective communications and connectivity with theater commands and other forces. It is desirable for stealth, acoustic search, and surface hazard avoidance to achieve this needed connectivity without requiring the submarine to be at periscope depth. The major communications frequencies used by the military today for tactical connectivity and force coordination are very high frequency (VHF), ultra high frequency (UHF), and above. These frequencies do not penetrate seawater, and therefore require an exposed antenna for high data rate reception and transmission. In addition, more and more connectivity is being achieved via geosynchronous satellite links, such as UHF satellite communications (SATCOM) and MILSTAR, which require at least modest antenna gain for link closure. As such, the submarine must expose an antenna of some type and size while operating at depth. Submarines are equipped with buoyant cable antennas (BCAs) that provide limited, receive-only communications at depth, but are not capable of UHF or higher-frequency two-way communications.

The Defense Advanced Research Projects Agency (DARPA), as well as the Navy, is pursuing advanced antenna techniques that would add two-way connectivity capability to BCAs. Such a capability would enable full and constant submarine connectivity to the emerging network-centric architecture without requiring periscope depth operations. This article provides a description of the DARPA Buoyant Cable Antenna Array (BCAA) Program and APL's role in it.

BCAA CONCEPT

The DARPA concept (Fig. 1) comprises a floating multi-element array deployed from the submarine that would provide two-way communications via SATCOM and line-of-sight resources. Satellites include existing and planned military systems (e.g., UHF SATCOM), as well as existing and emerging commercial satellites such as INMARSAT and Iridium. The towed linear array consists of advanced antenna elements, which, when beamformed, would provide the necessary gain for satellite and line-of-sight link closure. This linear beamformed array approach offers the added advantages of directional transmissions for increased stealth, noise cancellation and jamming resistance, and enhanced array gain via additional elements if needed.

Significant technical challenges exist, including needed array element gain and bandwidth in designs suitable for BCA adaptation, real-time multi-element adaptive beamforming in the presence of washover effects and array distortion, minimal signatures for maintaining stealth, and compact design to minimize ship installation and integration impact. A major issue with the floating antenna array concept is the exposure or washover characteristics of the array as it is towed along the sea surface by the submarine. In rougher seas, some elements will be washed over or shadowed, and will therefore be unable to contribute to array reception or transmission. As such, extra elements will need to compensate for these effects. Exposure behavior also affects array detectability and vulnerability. The Laboratory has extensive data from a previous Navy program that investigated the exposure of test arrays. That effort has provided valuable information for examining and predicting BCAA behavior, and is described in this article.

A joint team comprising Massachusetts Institute of Technology/Lincoln Laboratory (MIT/LL), the Naval Undersea Warfare Center (NUWC), and APL is supporting concept and technology development. MIT/LL

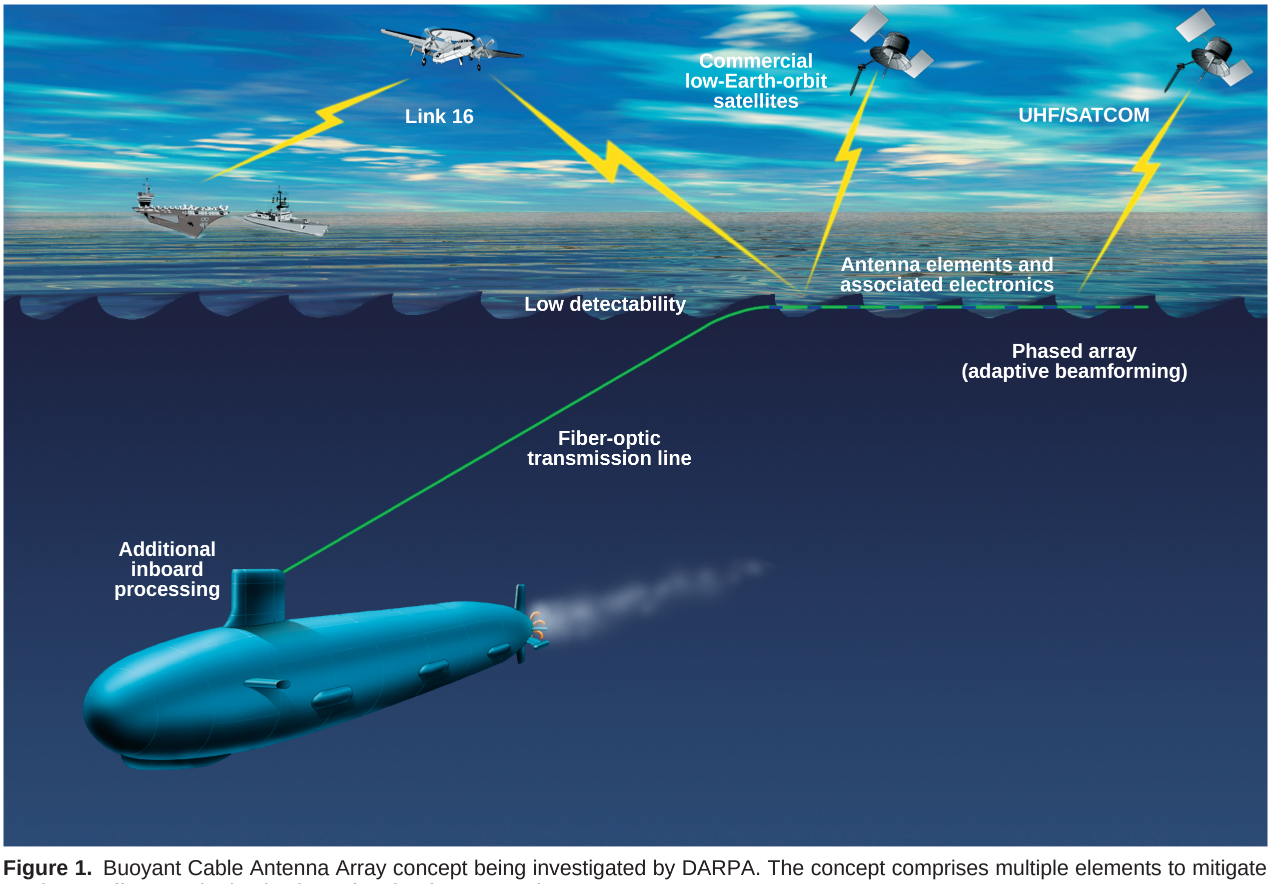

Figure 1. Buoyant Cable Antenna Array concept being investigated by DARPA. The concept comprises multiple elements to mitigate washover effects and adaptive beamforming for array gain.

is leading the array technology development effort for the DARPA program, including array element designs, dynamic adaptive beamforming techniques, and fiber-optic power and data transmission from the array to the ship. NUWC is providing an alternative single-element antenna approach. APL is primarily conducting critical array at-sea measurements, assessing array observability and vulnerability issues, developing overall system concepts, and examining higher-frequency capabilities and antenna technologies. A Memorandum of Agreement has been established between DARPA and the Navy in FY99 for joint assessment of these technologies.

ANTENNA TECHNOLOGY

To appreciate the magnitude of the technical issues involved in implementing submarine communications at typical patrol speeds and depths, consider the system shown in Fig. 2. The submarine is usually operating below periscope depth and at normal patrol speeds. To ensure that the BCA is at the sea surface, submarines may use a transmission line in excess of 305 m. A coaxial transmission line, such as those presently used, presents substantial RF losses (approximately 80 dB) and requires measures to provide intermediate amplification or a special low-loss feature such as a fiber-optic transmission path. (DARPA and the Navy are examining ways of increasing the operating speed and depth achievable by a BCA such as high-buoyancy or low-drag tow cable materials.)

In addition to the low-loss transmission line, the full operational concept depicted in Fig. 2 includes a conversion from RF to optical wavelengths and provisions for the necessary RF signal conditioning. RF signal conditioning is a final power amplifier or a low-noise amplifier for each transmit and receive antenna element. The number of antenna elements necessary to close the link with the satellite is a function of both the performance of the individual elements and the expected availability of each element, which we will discuss later in the article.

The goal is to produce an array that is both highly capable in terms of RF performance and small in diameter for ship stowage and covertness. A cavity-backed slot antenna (CSA) is cylindrical (similar to a transmission line buoyant cable) and offers the possibility of a small diameter at the UHF and L-band frequencies of interest. Since element performance is an issue, an ideal CSA would not be constrained in either length or diameter and would operate in a perfect ground plane with a gain of approximately 5 dBi. Constraining the diameter of the CSA introduces inefficiencies that reduce element performance. The CSA elements being designed by MIT/LL are of the order of 7.60 cm in diameter, which is electrically small relative to the approximately 1-m UHF wavelength. Smaller diameters may be possible, especially at other frequencies.

The antenna elements themselves represent a significant technical challenge. The Navy has supported previous development work in slender slot antennas, which has led to electrically small antenna elements configured in a "jelly roll" shape that forms a spiral cavity (Fig. 3).[3]

The spiral CSA is shown as an overlap configuration that in effect compensates for the small cavity diameter. Also shown are the supporting electronic components: the low-noise amplifier or final power amplifier, RF/optical transducer, and optical fibers. These components should be located near the spiral CSA for optimal performance. Also note that antenna elements farther down the array will require power and signal paths through the leading elements. This added consideration further complicates the development effort.

To date, the spiral CSA developmental effort has resulted in slender UHF antenna elements with measured performance that ranges from –4 dBi for a

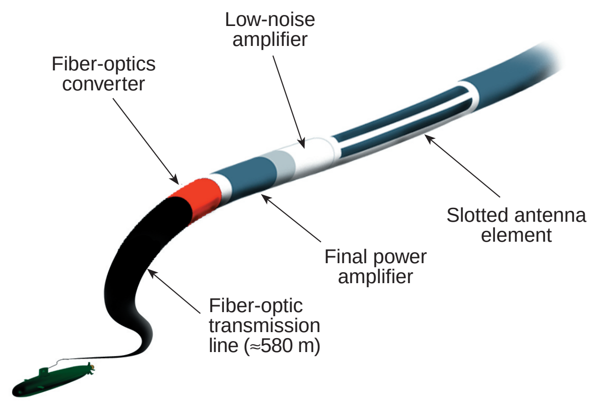

Figure 2. Conceptual configuration of a submarine BCAA.

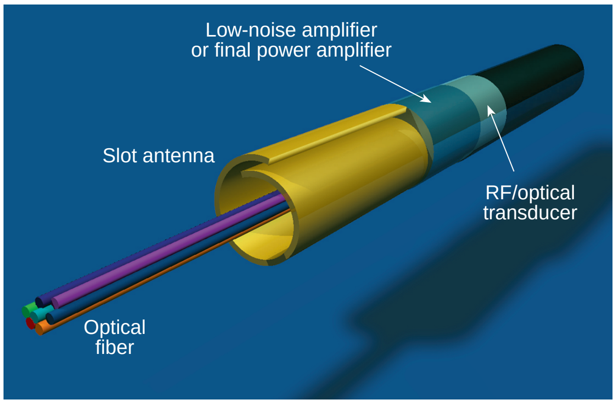

Figure 3. Conceptual design of the spiral cavity-backed slot antenna elements and electronics.

1.59-cm-diameter element to 0 dBi for both 2.54- and 2.86-cm-diameter elements. Note that these antenna elements are linearly polarized, whereas the Navy's UHF satellites are circularly polarized, which results in an added 3-dB signal mismatch loss (i.e., a net effective antenna element gain of –3 dB for the 2.54-cm-dia. element). As we will show later in the article, CSA elements operated in a linear array are believed to have sufficient performance to operate with the UHF Follow-on (UFO) satellite. Similar technology and design approaches may be used for potential higher-frequency (e.g., L-band) elements.

ARRAY DYNAMICS AND WASHOVER

The degree of buoyancy in a floating antenna is necessarily limited. Payload elements such as the actual antennas, the signal and power transmission lines, and electronics assemblies are composed of metals, plastics, and glass; the modest diameters of the housings (1.7–7.6 cm) constrain the volume available for added floatation materials. The specific gravity of the flexible buoyant antenna designs under consideration ranges from 0.4 to 0.7. A floating wire antenna also has very small exposed height or "freeboard." The largest cables considered, even floating two-thirds out of the water, protrude barely 5.08 cm above the ocean surface, much less than the wave heights associated with oceanic swells and comparable to the heights of locally created wind waves.

The resulting interaction with both wind waves and swell causes washover and the deformation of the cable (departure of its shape from a straight line through space). Cable deformation occurs on a scale comparable to that of the swell; the antenna-phasing process must account for this deformation to achieve the required antenna gain. Washovers are potentially more damaging to system performance since an element must be exposed, at least in part, to contribute to array performance.

Knowledge of the detailed behavior of buoyant arrays on the ocean surface is limited. Global statistics, such as the average exposed and submerged fractions and segment lengths for hundreds of meters of floating wire for a test array, were obtained in 1981. These measurements were sufficient to characterize antenna behavior at current low frequencies. However, for the short RF wavelengths encountered at UHF frequencies and above, a more extensive understanding of the washover behavior is required.

Figure 4 illustrates the behavior of a 1.7-cm buoyant cable test array under tow in a real seaway. The cable was specially prepared with white bands molded in to enhance visibility and provide a distance scale. The bands are 25.4 cm wide and spaced on 50.8-cm centers. Both the deformation and washover behaviors are very distinct. The sinuous shape shows some amount of deformation. The very bright white stripes indicate cable regions that are above the water, whereas the submerged portions of the cable are indicated by the distinctly darker (or absent) stripes. Although not easy to see in Fig. 4, the small-diameter buoyant cable does not float exactly on the ocean surface, but assumes a shape resembling an averaged version of the sea surface. The buoyant cable "rounds off" the extremes of the sea surface elevation, taking shortcuts through both the troughs and crests of the waves.

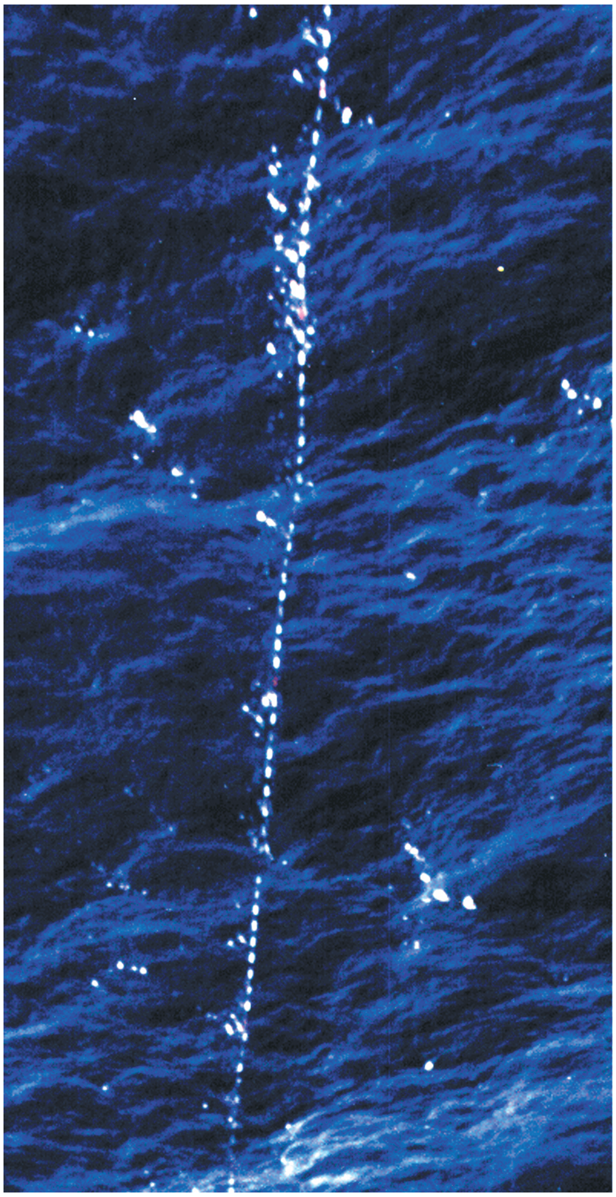

Figure 4. Instrumented buoyant cable test array under tow. The white bands, which were molded into the test antenna to enhance visibility, are 25.4 cm wide and spaced on 50.8-cm centers.

To gain insights, a simulation was developed consisting of a moving ocean surface and a moving floating cable responding to the buoyant forces exerted by that surface. The simulated ocean surface was derived from a sophisticated, two-dimensional ocean wave spectrum; the floating cable's response was modeled as a low-pass filter on the shape of the surface.[4] The filter characteristics for the floating cable were chosen to match the average exposed and submerged fractions observed during the test. The simulation, then, focused on floating cables with the same diameter (1.7 cm) and other characteristics. An extension to larger cable diameters is planned.

Figure 5 shows the simulation based on the test data. The cable is being towed to the right at 3 kt into a fully developed sea with an 8.2-kt wind. The alternating series of exposed and submerged lengths is shown, as is the position of the array relative to the sea surface. Note that the exposed regions do not lie on the sea surface, but are suspended a short distance above it.

The buoyant cable in Fig. 5 shows hypothesized locations of individual antenna elements within the array. The elements shown are 0.5 m long and are spaced at 1.5-m intervals, reasonable choices for a UHF system, with an RF wavelength of about 1.0 m. The key challenge posed by washover to the system designer is illustrated by the condition of the 13 antenna elements depicted in Fig. 5: 5 are completely submerged and another 2 are partially so, leaving only 6 available to transmit or receive at the instant shown. The array designer then must choose a number of array elements to build into the cable with the requirement that n of them contribute at any one time.

The required number of active elements n is determined by the array gain needed in the RF link budget (discussed later), but the number of elements required in the array m is set by the washover characteristics. The relationship of m to n can be explored by running the simulation that produced Fig. 5 for an extended period of time and tabulating the results. Figure 6 is a map of simulation output showing the exposure status of each array element during a 3-s period.

The active elements are indexed horizontally in the figure, and time goes from bottom to top. The gray scale value for each element and time shows the fraction of the 0.5-m length of the exposed element. Note that only the active elements (the dark bands of Fig. 5) are shown; the intervening parts of the cable are not represented in Fig. 6. Each element exposure (the vertical white bars) lasts about 1 s; the submerged intervals (vertical black bars) last somewhat longer. At the start of the interval, about 15 of the 50 elements are completely exposed; the exposure status of the elements changes frequently, and at the end of the interval about 13 are completely exposed. All but a few of the 50 elements are completely exposed at some point during the interval, but no element is completely exposed for the entire interval. Thus, a receiver design for a BCA communications system must either be robust against such rapid changes or adapt to them.

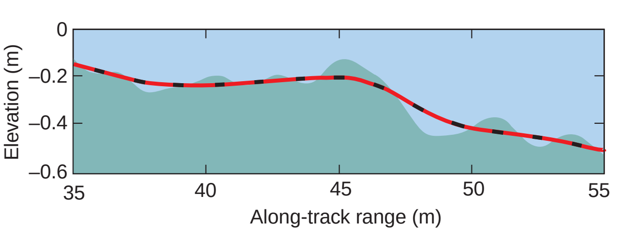

Figure 5. Simulation of a 1.7-cm array being towed through a rough sea surface, which causes some elements to be exposed and others submerged. (Red portions of curve = wire, black = antenna elements.)

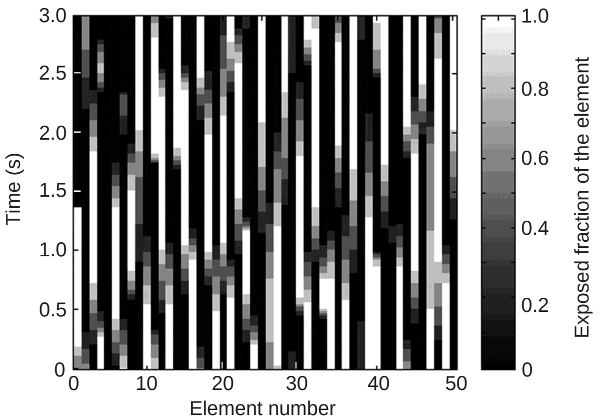

Figure 6. Exposure map for the antenna elements of a 1.7-cm test array towed at 3 kt away from an 8.2-kt wind sea. The gray scale shows the fraction of each active element that is exposed.

Current BCA-sized designs for UHF communications would require the gain from multiple antenna elements to satisfy the link budget. Therefore, statistics on the number of elements out of the water at any given time are of great interest. If the simulation from Figs. 5 and 6 is extended to an interval of several thousand seconds, the temporal statistics of the number of exposed elements can be tabulated. The result for the available antenna gain for a BCA-sized array with 50 instrumented elements is shown in Fig. 7. The available antenna array gain is related to the number of exposed elements by $G = 10 \log n$, where G is the maximum gain available from the phased array, and n is the number of elements exposed and participating in the array.

For this case, 9+ dB of array gain (8 or more elements exposed) is available almost 99% of the time, and 10+ dB (10 or more elements exposed) is available 95% of the time. Statistics such as these are used by the designer in folding the washover properties together with the properties and requirements of the communications system in order to select the number of elements for the aperture. Other statistics that can be computed on the basis of the simulation include fade duration (the average length of time that the gain spends below a given threshold) and element statistics such as the distribution of the duration of individual element exposures and submergences.

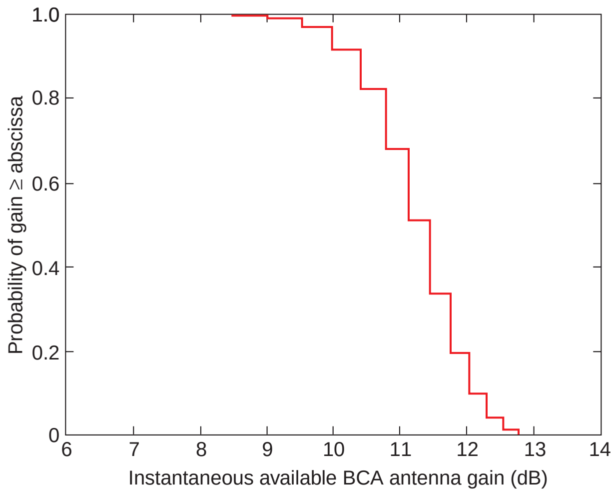

Figure 7. Distribution of available antenna gain due to washover for a 50-element 1.7-cm array in an 8.2-kt wind, downwind tow.

The simulation used in the previous description is tied to 1.7-cm-diameter cables because it employed measurements of 1.7-cm test array behavior to set the cable's response to the ocean surface. The biggest difference between a 7.6- and a 1.7-cm cable is the added freeboard of the larger cable. This should lead to better exposure characteristics for 7.6-cm-diameter cable arrays. Anecdotal evidence from very short data segments taken under the DARPA BCAA Program in 1998 supports this observation. The trade-offs with larger diameters include ship impact and possible differences in observability.

UHF SATELLITE COMMUNICATIONS

Military UHF SATCOM relies principally on the UFO satellite system as well as some legacy capability on the Fleet Satellite (FLTSAT) System. These systems have three segments: space, ground or terminal, and control.

The UFO space segment consists of eight satellites in geosynchronous orbit above the equator, with two satellites working simultaneously in one of four operational areas. Each UFO satellite has 39 UHF communications channels: 1 antijam uplink broadcast channel, 17 wideband channels (25-kHz bandwidth), and 21 narrowband channels (5-kHz bandwidth). Each wideband and narrowband channel uses a separate transponder to receive, frequency translate, and amplify signals within the channel. As such, these transponders are often referred to as bent pipes.

The ground segment comprises fixed site, ship, submarine, aircraft, ground mobile, and man-portable terminals. Terminals consist of RF equipment (antennas, diplexers, low-noise amplifiers, power amplifiers, radio transceivers) and baseband equipment (modems, cryptographic equipment, voice/data user equipment).

The control segment consists of both satellite and communications control. Satellite control is provided by tracking, telemetry, and command subsystems that are compatible with the Air Force Satellite Control Network. Communications control is provided by the Joint (UHF) MILSATCOM Network Integrated (JMINI) Control System. JMINI implements demand-assigned multiple-access (DAMA) operation, which allows one channel to support multiple communications requirements simultaneously. This mode of operation also allows satellite resources to be assigned to services according to a schedule (preassigned service) or based on a request for service from a user (*ad hoc* service). When a communications service is no longer required, its resource is made available for another service. DAMA also allows preemption of one communications service to support another higher-priority requirement. The DAMA mode of operation allows many more communications requirements to be satisfied than possible using today's methods by centrally controlling user access to the UHF MILSATCOM channels.

System Performance

The system performance of UHF SATCOM data links is quantified in a link budget. An example of a link budget for a seven-element BCAA is shown in Table 1. Here, it is assumed that a shore station is sending data to the BCAA using a 25-kHz channel on a UFO satellite. The shore station is characterized by its effective isotropic radiated power (EIRP), which includes the terminal power amplifier, antenna gain, and various losses. The satellite is principally characterized by the receive gain-to-noise temperature ratio (G/T) and EIRP. However, the satellite produces two secondary effects in the link budget; the use of a hardlimiter at the input to the transponder causes a 1.1-dB processing gain, and the use of right-hand circular polarization causes a 3-dB mismatch with the linearly polarized spiral CSA. The BCAA is characterized by the peak element gain and gain derived from arraying these elements.

Once the characteristics of the individual elements in a link budget are known, that satellite link is broken into its two components: uplink and downlink. For each component, carrier power-to-noise power density (C/N_0) computations are made. These are simple additions and subtractions if all the elements are in decibels. The total C/N_0 is then assessed by combining the uplink and downlink C/N_0 quantities as

$$\frac{C}{N_0}_{\text{total}} = \left[\left(\frac{C}{N_0} \right)^{-1}_{\text{uplink}} + \left(\frac{C}{N_0} \right)^{-1}_{\text{downlink}} \right]^{-1} .$$

Table 1. UHF satellite link budget.

Parameter	Units
Shore station-to-satellite uplink	
Shore station EIRP[a]	26.8 dBW
Uplink propagation loss	−174.0 dB
Processing gain	1.1 dB
Boltzmann's constant^{-1}	228.6 dB/K/Hz
Satellite G/T[b]	−16.0 dB/K
Uplink C/N_0[c]	66.5 dB
Satellite-to-BCAA downlink	
Satellite EIRP (25 kHz)	26.0 dBW
Downlink propagation loss	−173.0 dB
Nominal peak antenna element gain	−0.9 dBiL
Polarization mismatch	−3.0 dB
Array gain (10 log *n*)	8.5 dB
Noise temperature of BCAA^{-1}	28.0 dBK
Boltzmann's constant^{-1}	228.6 dB/K/Hz
Downlink C/N_0	58.2 dB
C/N_0 total	57.5 dB

[a]EIRP = effective isotropic radiated power.
[b]G/T = gain-to-noise temperature ratio.
[c]C/N_0 = power-to-noise power density.

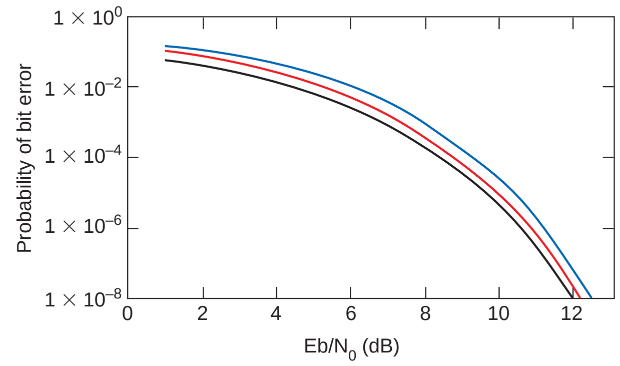

Figure 8. Probability of bit error versus energy per bit-to-noise power density (Eb/N_0) for three transmission types: binary phase shift keying (black curve), differentially coherent phase shift keying (red curve), and differential phase shift keying (blue curve).

An important measure of performance for digital communications is the probability of bit error P_E. As shown in Fig. 8, P_E varies with energy per bit-to-noise power density ratio (Eb/N_0) and by modulation type. Recognizing that C/N_0 is related to Eb/N_0 by $C/N_0 = (Eb/N_0)R$, where $R = 1/T$ (bit duration) or bit rate, we can relate the C/N_0 derived in the link budget to P_E. Alternately, a P_E can be specified, and the C/N_0 that is available for communications as determined by the link budget can be compared to the C/N_0 that is required to support the particular data rate and modulation type. The difference between these two C/N_0 values can be considered margin.

As an example, consider Fig. 9, where the communications scheme uses differential phase shift keying (DPSK) modulation and a 10^{-5} P_E is adequate. Using the link budget already derived, we can see that the link margin is 3.4 dB for a communications rate of 24,000 bps.

Orientation and Washover Effects

The link budget computed in Table 1 was made under ideal conditions that assumed that the peak element gain was oriented toward the satellite and that there were no communications channel degradations. Under operational conditions, element gain in the direction of the satellite will be reduced relative to peak as angle varies from zenith and azimuth angle varies from broadside. Currently designed BCAA elements have an approximately 3-dB orientation loss for operational conditions where the angle from the horizon (elevation angle) is 10° and the angle from broadside is 30°.

Communications channel degradations will result from washover or other environmental effects. In this regard, washover represents the biggest concern. As a first-order approximation for communications modeling, we will model the output of the BCAA beamformer as a random variable. Power measurements made during at-sea testing will form a probability density function for a given set of sea states and headings with respect to the seas.

P_E estimations of simple modulations can then be made using simple continuous-wave (CW) measurements from the satellite:

$$P_E = \int_0^\infty P\left(E \middle| \frac{C}{N_0}\right) P\left(\frac{C}{N_0}\right) d\left(\frac{C}{N_0}\right),$$

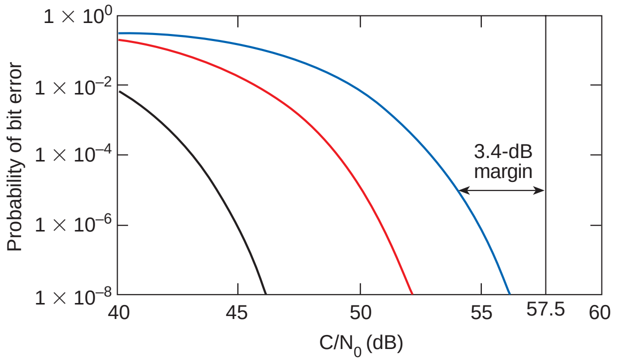

Figure 9. Probability of bit error versus carrier power-to-noise power density (C/N_0) for three bit rates: R = 2,400 (black curve), 9,000 (red curve), and 24,000 (blue curve) bps.

where

$$P\left(E\middle|\frac{C}{N_0}\right)$$

is the P_E given input C/N_0, and $P(C/N_0)$ is the probability density function of the measured power after accounting for the noise power density of the receive system. For DPSK modulation,

$$P\left(E\middle|\frac{C}{N_0}\right) = 0.5e^{-\left(\frac{C}{RN_0}\right)}.$$

Thus, for a given rate R and sea state conditions, P_E can be estimated.

This simple method has many limitations, however, the greatest being that the characterization must fully describe P_E. Some modulations, such as coherent phase shift keying, would arguably fail this criterion, since the phase reference will often be lost after an outage of limited duration. Once this reference is lost, the new reference can lock incorrectly and subsequent bits will all be decoded erroneously.

Similarly, the method can not be simply extended to include the effects of commonly used forward error control coding techniques such as Viterbi coding. Convolutional coding with Viterbi decoding is ideally suited to an additive white Gaussian channel where errors occur randomly. Washover will cause burst of errors that could easily exceed the error-correcting ability of the code. It may be possible to model the burst errors by accounting for the washover as a joint distribution that includes both fade depth and fade duration.

FY99 AT-SEA TESTING

Figure 10 depicts the FY99 DARPA test of BCA experimental technologies, just completed in May–June 1999. The purpose of the test was to obtain side-by-side measurements from the MIT/LL BCAA and the single-element Low Profile Antenna (LPA) being developed by NUWC. The test was performed in the waters off the Pacific Missile Range Facility (PMRF) on the island of Kauai.

The primary objectives of the test were to measure and compare the following key link budget parameters:

- Elevation loss as a function of elevation angle under a variety of environmental conditions. Elevation loss is governed by such factors as the interaction of the antenna pattern with the moving ocean surface, the pitch and yaw of the antenna elements as seen at low grazing angles, and the increased effect of water droplets and water lapping at the lower angles closer to the ocean surface.
- Link margin and sustainable data rate using actual satellite signals under a variety of environmental conditions in a realistic open ocean environment. The UHF FLTSAT situated over the continental United States will be used, with both CW and modulated waveforms. Variability in the environmental conditions is to include sea state, headings with respect to the seas, and tow speeds that are as representative as possible of expected operational conditions.

Secondary objectives included an initial, qualitative assessment of the observability of the two systems, primarily by visual and infrared means; the collection of data to characterize statistically element washover and antenna availability; and the collection of data to allow extrapolations of the expected performance of variants and hybrids of the two systems. As indicated in Fig. 10, video and IR measurements were conducted from a helicopter and from a high-resolution automated tracking camera on shore.

The PMRF was selected because of the 457-m-cliff site on Makaha Ridge on the western shore of Kauai, which provides an unobstructed path from the shore-based UHF transmitter to the antennas being towed in the waters below at relatively steep elevation angles of up to 30°. Measurements from the FLTSAT were conducted in open ocean waters in the PMRF locale. Predominantly receive-only testing was done; side-by-side testing was performed so that simultaneous measurements could be obtained from both experimental systems under the same operational conditions, and so that the performance of the two experimental techniques could be compared using like measures of performance. Port and starboard outriggers were installed for simultaneous side-by-side testing of both systems.

Environmental Characterization

An accurate assessment of the environment was key because the performance of the systems was expected to be highly dependent on factors such as sea state, significant wave height, and the direction of tow with respect to the seas. Environmental data were collected by two principal systems: a directional wave buoy and a scientific-grade meteorological system. The wave buoy is a deployed system that collects directional wave spectral data while in the water, and continually transmits these data to the ship via an RF link. The directional wave spectral data will allow an accurate assessment of sea state and significant wave height by use of the Wave Identification and Tracking System (WITS)[5] onboard the US *NohoLoa* to analyze each 0.5-h segment of data. The meteorological system provided wind speed and direction, air and sea surface temperature, relative humidity, and barometric pressure. The wind speed data will allow an alternate assessment of sea

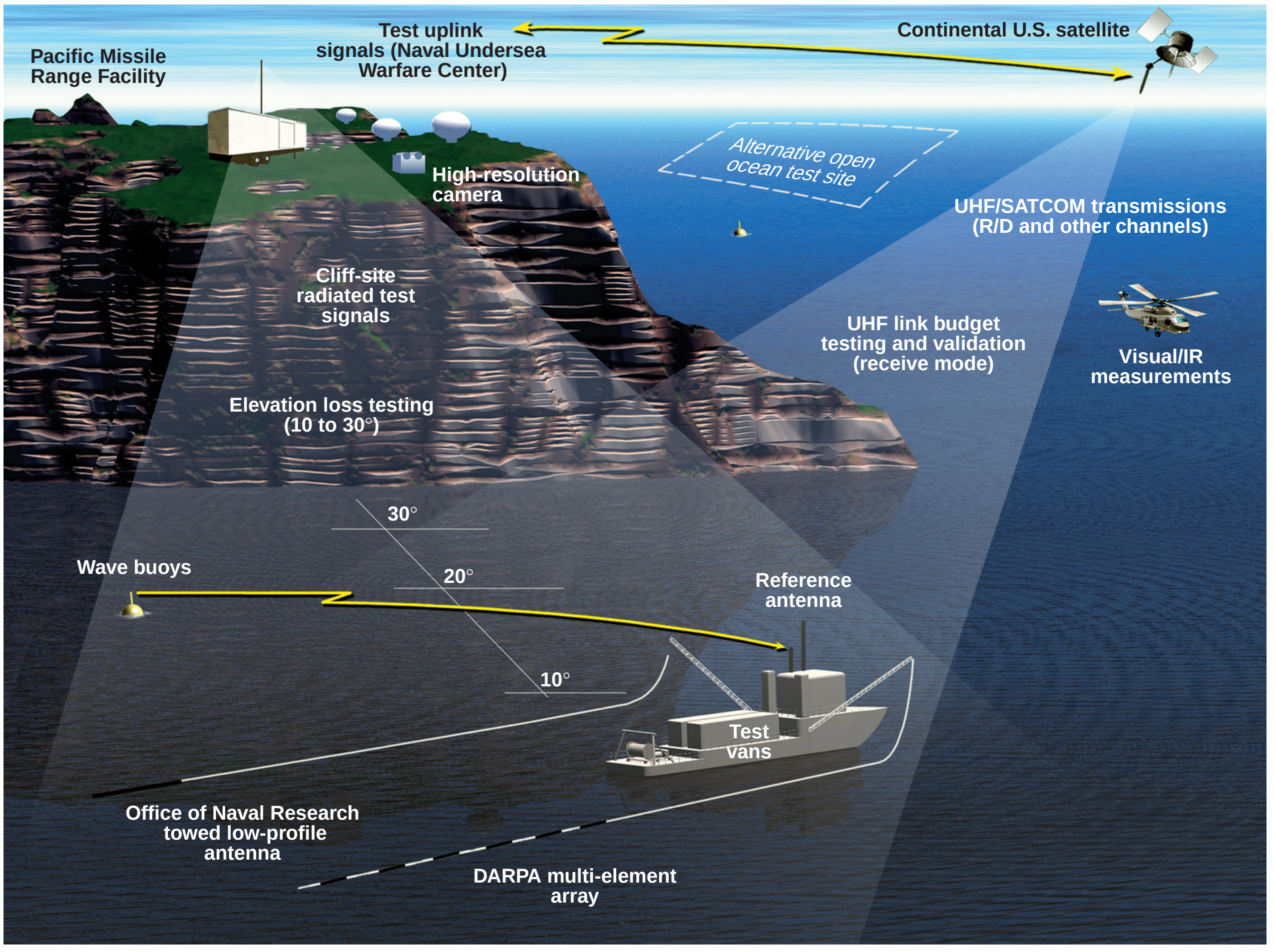

Figure 10. An overview of the DARPA BCA technology test, showing both the elevation loss and UHF link budget test components conducted in Hawaii during May and June 1999.

state. Additionally, photographs taken every 30 min will provide a visual record of the sea state.

Test Matrix and Run Description

A fundamental objective of the test was to measure elevation loss and link margin under a variety of conditions expected to span the range of actual submarine operating conditions for the communications system. Table 2 lists the conditions under which measurements were to be made, both for the elevation loss and link margin components of the test. The principal parameters to be varied were:

- Antenna tow heading with respect to the direction of the dominant wave component of the seas
- Elevation angle from the antenna to the satellite (or ridge) transmitter
- Sea state
- Tow speed of the antennas through the water
- Angle to the transmitter relative to the antenna broadside

Figure 11 then shows a subset of the runs for the elevation loss testing, illustrating the differing elevation angles from the shore, orientation to the seas, and differing reception angles. The BCA elements have a very significant falloff in gain as the angle incident to the antenna progresses away from broadside. Most of the testing was conducted near broadside, and most of the results normalized to broadside so that meaningful, well-characterized comparisons could be made across the other parameters in the test matrix. However, some data were collected at angles of up to 50° from broadside to obtain a good, albeit less complete, performance characterization under those conditions. Runs were conducted over multiple days to capture the different sea state/swell combinations of interest.

Measurement Overview

The test measured the following significant data in addition to various environmental parameters already described.

Table 2. Parameters defining the operational conditions under which the BCAA will be expected to function.

Parameter	Conditions to be measured
Heading with respect to seas	0, 45, 90, 135, 180°
Elevation angle	10 and 20° (some also at 5, 15, and 30°)
Sea state	1.0, 2.5, and 4.0
Tow speed	4 and 7 kt
Angle from broadside	Broadside ±20° (and others)

- Raw and sampled baseband I and Q signals received by the individual elements of the BCAA, LPA, and BCAA beamformer. These recordings will allow post-test playback of any of the raw test data.
- Power measurements of the BCAA, LPA, and the reference receiver onboard *NohoLoa*. These data will be used to characterize elevation loss, link margin, and washover statistics.
- Bit error rate (BER) and block error rate statistics for each system taken while receiving digital BER waveforms during the satellite portion of the test. These data items will be used to measure the data rates that can be supported under the various test conditions.
- Video and IR measurements. This information will be used for vulnerability assessment as well as to observe antenna tow characteristics and corroborate the washover data.
- Latitude, longitude, heading, and speed. These data were collected using a differential Global Positioning System throughout the test.

Both CW and modulated BER waveforms were transmitted from the satellite at various data rates using a specialized modem designed to mitigate the effects of washover by extended interleaving as well as a more standard modem commonly used by the Navy. The CW waveforms will be used to provide a measure of link margin; the BER waveforms will be used to corroborate the sustainable data rates implied by these link margins and to demonstrate system performance using real signals.

Planned Results

The test was successfully completed in June of this year. Data analysis is under way. A measure of elevation loss, link margin, and sustainable data rate will be reported for each operational and environmental condition examined during the test. Elevation loss will be computed by comparing the power level received at the elevation angle of interest with that received at the reference elevation angle, which is directly overhead. The received power level at the elevation angle and conditions of interest will actually be a probability distribution function (PDF); therefore, elevation loss measures for the mean (i.e., 50%) and the 90% levels of the cumulative distribution function will be reported. The received power level at the reference elevation angle will be determined under calm conditions at a reasonably high angle, which will then be normalized to a 90° overhead elevation angle by use of the measured antenna element beam pattern. Link margin will be computed using the CW satellite transmissions for prescribed modulation techniques, data rates, and bit error rates. The PDF giving the CW signal-to-noise ratio, corresponding to C/N_0, will be measured and plotted to overlay the curves shown in Fig. 10. With the use of the joint PDF integral described earlier, the link margin to be reported will be identified.

Sustainable data rate will be determined in two ways. The first will be to transmit a number of different data rates over the satellite channel, measuring the BER for each and selecting the data rate providing a BER closest to 10^{-5}. The second will be to determine a BER from the link margin

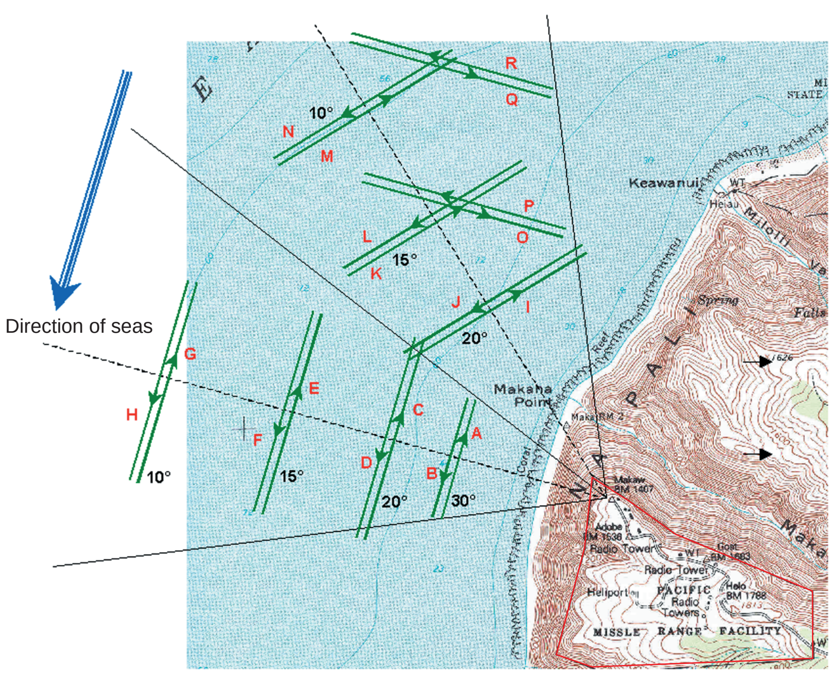

Figure 11. Run segments along which the antennas are to be towed during the elevation loss component of the test. These run segments are designed to capture 10 min of data under each condition of interest.

measurement by using curves such as those shown in Fig. 10. This will be accomplished by specifying a minimum acceptable link margin and then selecting the data rate curve that satisfies the link margin. These two measures of sustainable data rate will both be reported and are expected to agree fairly closely.

SUMMARY

DARPA and the Navy are pursuing advanced BCA technologies that could dramatically enhance submarine connectivity at speed and depth and overcome current constraints that require periscope depth and more exposed operations. Significant technical challenges exist, which are being examined by DARPA and the Navy, with a major joint field test of candidate technologies just completed in FY99. APL is assisting both DARPA and the Navy in the development, testing, and evaluation of this potentially important technology to the submarine force.

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