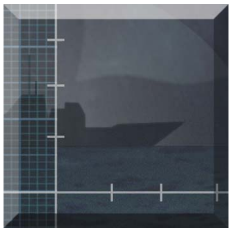


Operational Evaluation for Evolutionary Sonars

Bradley O. Bates, Rory Calhoun, and David E. Grant

Development of passive sonar systems has undergone a renaissance during the last 10 years. Commercial off-the-shelf (COTS) hardware, based on ever more powerful processors, has changed the time line for development of a new sonar system from decades to a few years. Programs like the Advanced Processor Build and the Acoustic Rapid COTS Insertion (ARCI) have made significant improvements possible. Operational test and evaluation must go through a similar renaissance to support these shorter development times. In this article we present an approach for early involvement in operational testing and its application to the Advanced Deployable System and the ARCI program. We show examples from these programs that illustrate how system performance can be assessed with limited test time and resources.

INTRODUCTION

Imagine that you have just completed a 12-hour end-around maneuver to place your submarine in firing position against an enemy tanker. You have defeated the destroyer escort screen and are ready to raise the periscope to set the firing bearing. “Final bearing and shoot, number one scope. Up scope,” you order. Once the bearing is entered and checked, “fire one . . . fire two . . . fire three . . . fire four.” You hope that at least one weapon will find its mark and explode, though your experience suggests that all will hit without detonating. Tense minutes pass in what seems like an hour until the calculated time of impact has long passed. Nothing! Nothing, that is, except for the escort that is now bearing down on your position, black smoke billowing from its stack, with a zero angle on the bow. Your reward for completing a textbook approach is to endure and hopefully survive a depth charging by an adversary you are powerless to attack.

Stories like this were not uncommon during the early years of World War II. But it was not until ADM C. A. Lockwood Jr. had the submarine USS *Muskallunge* fire three Mk 14 torpedoes at a vertical cliff on the south side of the Hawaiian island of Kahoolawe on 31 August 1943 that the problem was understood. Two torpedoes exploded and a third was a dud. Upon recovery and disassembly, personnel found that the firing pin had struck the firing cap with insufficient force to set it off. Further investigation revealed that the design of the firing mechanism was not rugged enough to withstand the distorting force of deceleration from torpedo impact.

Shortly thereafter, Congress enacted legislation that established operational test agencies for each of the service branches whose charter it was to conduct operational testing on all new weapons systems.

These agencies were tasked to evaluate the operational effectiveness and suitability of the systems being developed for use by operational forces in harm's way.

For many years, operational testing followed the lead of those early testing pioneers and focused on evaluating the performance of an end product once it was turned over by the developer. As one would imagine, this arrangement led to animosity between the developer and tester, created schedule and financial problems when tests went poorly, provided operational feedback to the developer only after it was much too late to economically implement lessons learned, and heavily tasked operational forces to provide manpower and test assets to support the "graduation exercise."

By 1996, a new challenge to sonar system operational testing had emerged. Efforts to regain and then maintain submarine acoustic superiority resulted in the development of an acquisition program known as Acoustic Rapid Commercial Off-the-Shelf (COTS) Insertion (ARCI). Under this initiative, technology insertions would be made to submarine sonar systems on a rapid, periodic basis (every 1 to 2 years) to ensure hardware currency, software capability would be updated rapidly (through an initiative known as the Advanced Processor Build [APB] program), logistics costs would be effectively contained, and almost immediate performance improvements would be realized. The goal was to complete a four-step process to final configuration in about 3 years (as opposed to the conventional acquisition time lines that exceeded 10 years from inception to completion).

The ARCI program was one of the first large-scale efforts designed to take advantage of new acquisition directives that encouraged execution of evolutionary acquisition strategies. It was up to the sponsor, developer, Navy type commanders, and operational test agency to devise a relationship and strategy that would meet the needs of all the stakeholders.

Operational evaluation assesses the effectiveness and suitability of a system to support a decision for readiness for Fleet introduction. The traditional approach to operational testing involves a test team that is introduced to the program shortly before the test and then observes the system in operation. Generally, the test team's assessment is interpreted as a go/no-go decision and there is little insight into why a certain performance is observed. Limited test time and test assets exacerbate this shortcoming to operational testing. The observed performance for the limited test may not represent the true capability. Currently, the Navy is exploring ways to improve the test strategy by early involvement in program development and by including Navy and University Affiliated Research Center laboratories and systems developers, in a limited way, in the evaluation team. This approach helps the evaluation team to develop a better understanding of program goals, helps the development team stay current with program needs, ensures that the test team will retain objectivity, and fosters trust between the evaluation and development teams.

In this article we address the evolving roles in system analysis, the advantages of acoustic post-analysis, and the way beam noise collected during operational test is used to determine the detection footprint of the sensor under test.

TESTING PHILOSOPHY

Historically, government test agencies were seen as organizations that conducted pass/fail testing of a system's ability to function effectively and suitably in an operational environment; the command did not participate in a program until the engineering development model was completed and ready for technical evaluation by the government sponsor. However, other responsibilities were subsequently added that tasked the testers to become involved in a program early enough to assess (1) potential operational effectiveness and suitability of a system and make recommendations regarding programmatic decisions other than Fleet introduction, and (2) operational effectiveness and suitability regarding Fleet introduction decisions. Given the nature of the evolutionary development of the build-test-build model used today by both the submarine and surface combatant communities, government test team involvement must not only begin earlier, but must also be continuous in order for the command to contribute meaningful and timely analytical feedback regarding operational suitability.

A sponsor's development team comprises personnel from multiple government agencies and supporting laboratories who have the required level of technical understanding. The active duty members of the test team are drawn from Operational Test Directors (OTDs) and their support staff, who serve on a 2- to 3-year rotation basis. These active duty participants may lack the formal education required to understand the complexity of the complete sonar system undergoing evaluation. However, they bring military experience that is valuable in providing a clear picture of current Fleet operations and future operation needs. Through early involvement in the process, the government test agency takes advantage of the other participants' understanding of the system and develops relationships with team members. This enables the command to select timely and credible input sources for reports on operational suitability.

Because an OTD works with multiple programs, he or she can provide invaluable insight from experiences with those other programs. The OTD can also give the program office a unique perspective on how the particular system could benefit from achievements or problems in other systems. This broader perspective helps prevent connectivity and interoperability issues at an early stage so that cost-effective corrective action can be taken.

Government test agency participation in test and evaluation integrated product teams and associated working groups helps facilitate the evolution of the program testing strategy. Together, the government test agency and the program office can identify particular data so that plans can be designed to collect them and software can be adjusted to ensure that the information is readily obtainable. Close involvement of the government test agency with the program office also ensures that the test philosophy evolves efficiently as the program evolves. The synergy that develops from this working relationship leads directly to economies from shared data, shared test assets, and shared analysis efforts.

Involvement of the government test agency must add value to the program office endeavor to develop the system. This "value added" is most readily observed in terms of direct technical feedback; assistance with Operational Requirements Document (ORD) and Test and Evaluation Master Plan development and revision; interfacing with the end user; and participating on one or more technical teams. As a result of this participation, the OTD learns what the program needs in terms of products from the government test agency, keeps the program abreast of tester concerns with respect to operational effectiveness and suitability issues, and resolves testing concerns before they become real problems. The OTD can also provide the program office with independent thought to help solve technical and programmatic problems.

Decisions concerning operational effectiveness and operational suitability in earlier testing relied largely on comparing tabulated test data to system performance requirements. However, it was not always apparent that a sufficient sample size was obtained to make statistically supported pass/fail decisions. Limitations to operational test times highlighted a previously obscured issue, i.e., statistical significance in test data.

A new initiative grew from this realization. It was obvious that sufficient test time to obtain statistically significant data for evaluation of performance parameters (e.g., search rate, detection range, etc.) directly related to the goal of reaching and maintaining acoustic superiority would never be achieved. Two alternatives were investigated to supplement direct test results: (1) use a statistical sampling methodology known as "bootstrapping," or (2) test for understanding by recording defining environmental, target, and test platform parameters, then analyze those data in an acoustic laboratory once the test was completed to look for reasons that would explain observed system behavior. The second alternative was chosen since it was deemed to require fewer at-sea hours than the bootstrap method and because the test-for-understanding methodology could directly support system improvements since direct causes for successes and failures could be identified.

To minimize the cost of the test-for-understanding approach, analysis efforts were teamed with the acoustic analysis programs at APL. The Environmental Sciences Division at the University of Texas Applied Research Laboratory provided acoustic performance modeling and acoustic environment analysis support in this effort. NAVSEA Keyport Division and its Lua Lua Lei Detachment in Pearl Harbor, Hawaii, provided operational test support. To date this team has provided invaluable feedback to the ARCI and APB development efforts, effectively supported formal ARCI operational testing, and given COMSUBLANT and COMSUBPAC crucial operational insight into expected system performance aboard their submarines.

ANALYSIS OF ACOUSTIC PERFORMANCE

As previously noted, the purpose of operational testing is to ensure that the system under test meets or exceeds the performance parameters stated in the ORD. In evaluating an evolutionary system it is also necessary to identify the possible points of failure such as system response, system operability, operator training, operator performance, and environmental conditions during the conduct of the test. Correct feedback of the point of failure to the Navy Program Manager and Pentagon acquisition sponsor allows timely decision making regarding the future program direction. Should money be invested to improve the hardware, software, or logistical support? Which investment will result in the greatest increase in system performance?

The best method to verify sonar system performance is by establishing ground truth through acoustic post-analysis. Experienced acoustic analysts with system test experience should conduct acoustic reconstruction. This analysis must be performed on the system under test or an exact equivalent. Beam noise from the sonar system being tested must be collected to support "footprint" analysis. (The footprint is the irregularly shaped area around a sensor where detection is possible.) An investment by the government program manager is required to establish a system testbed and to allow the test agency to contract with the necessary acoustic analysis and signal processor experts to complete the analysis. The system testbed must be able to host the system under evaluation and must undergo technical refresh to keep pace with system development. It must also be identified as a priority for the prime system integrator to ensure timely completion of acoustic analysis.

Ground Truth Through Post-Exercise Acoustic Analysis

Establishment of ground truth using post-exercise acoustic analysis does not replace the use of physical reconstruction, but rather uses the physical reconstruction as a starting point. Attempting to do post-exercise acoustic analysis without reconstruction would leave the analyst with many of the same problems inherent with relying on real-time contact detections as absolute truth. Post-analysis allows the analyst to take advantage of knowing where in azimuth and range the exercise contact is and identifies contact behaviors such as speed, depth, and propulsion mode changes, which help to verify that the sources detected are, in fact, from the exercise contact and not from interfering contacts.

First pass analysis is conducted using the sonar system under evaluation in the most sensitive lineup. This lineup may not be feasible for real-time search because of display overload, but it takes advantage of high-resolution verniers and optimum update rates. This pass will be used to establish what sources from the contact of interest are detectable on any of the system displays at an operationally significant range and will answer the most basic question: Can we detect the contact with our current array and processing technology? Because the lineup used for first pass analysis is not necessarily feasible for real-time search, only a cursory comparison is made between the post-analysis results and real-time operator detections.

Second pass analysis is performed with the system configured in accordance with current operational guidance. If such guidance has not been formalized, the second pass is made with the system configured in accordance with the evaluation platform's search plan. The primary objective of second pass analysis is to determine if the contact of interest is detectable on the system search displays when the system is operated in accordance with current operational guidance. System performance during second pass analysis and real-time operator detections are compared to determine if current operational guidance helps the operator detect the contact of interest. Operational test personnel observations address issues such as whether the search plan was generated using the current guidance, and whether the search plan was adhered to during the evaluation.

When post-analysis shows that contact sources—available to the operator when the system under evaluation was operated in accordance with available operational guidance—were not detected in real time, it is necessary to look at operator training. These questions must be asked: Did the operators receive training in the proper operation of the system? Were the operators familiar with the test contact acoustic vulnerabilities? Did the search plan support contact detection? Observations by the embarked test team can provide valuable feedback to Navy training commands and commands tasked with developing operational guidance. The embarked test team also makes observations regarding watch stander discipline, operator alertness, and watch station communications.

Operational Evaluation Data Sets

Sonar performance is evaluated using many measures of effectiveness including probability of detection (P_d), probability of false alarm (P_{fa}), and total holding time (H_t). H_t is calculated by measuring the difference between the time of initial contact detection and the time of contact fade or loss using any source radiating from the exercise contact. Figure 1 illustrates the difference in H_t, for four recent sonar evaluations, between maximum system performance as measured during post-analysis and system performance during real-time operations. H_t is shown as a percentage of contact availability as defined by the exercise contact physically contained in the exercise area.

If H_t was used to evaluate the system under test in Fig. 1, only Test 2/Contact 2 and Test 4/Contact 1 would provide a relatively accurate measure of system performance. For the other test and contact combinations, the error is sufficient to push system performance outside the key performance parameter (KPP) specified in the ORD. Failure of a system to meet a KPP could result in that system being determined as not operationally suitable and therefore unlikely to be introduced into the Fleet; the funding and time invested in system development would be wasted. Post-analysis may show that the system under evaluation does, in fact, meet the KPP as specified in the ORD and that further evaluation of the system is warranted.

For all four of the systems evaluated through post-analysis, the primary reason for poor real-time performance was determined to be operator training and contact familiarization. In Test 1, Contact 1 had a malfunctioning noise augmentation unit; therefore, the radiated sources were off in frequency by a difference large enough to cause the operator to dismiss the contact as an interferer. In Tests 2 and 3, Contact 1 was undetected by the watch team and, though post-analysis was unable to determine a definite cause, contact recognition and an incomplete search plan were believed to be the likely points of failure. In Test 4, the watch team was unfamiliar with the exercise contact and dismissed or downgraded hours of valid contact holding.

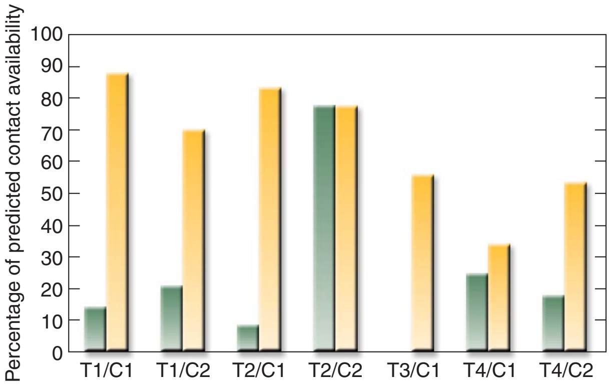


Figure 1. Total holding in real time (green) versus post-analysis (orange) (T = test, C = contact).

UNDERSTANDING SYSTEM PERFORMANCE THROUGH FOOTPRINT ANALYSIS

The ultimate test of a new or improved sonar system is the measurement of acoustic performance. Examples include sensor detection range, towed array sweep rate, and, for a distributed surveillance field, the probability of detecting a target within a certain time window. A direct measurement of detection range might involve closing and opening the range between a target and receiver and noting the ranges at which the operator gains and loses the target. In a distributed field, one may count the number of times or how often an operator detects a target within a given time period.

Time allotted for testing is often limited so that observations from such tests yield a small sample set. Various statistical gymnastic operations can be applied, including the so-called bootstrap methods; however, a small sample set cannot provide information that does not exist, and the uncertainty in estimation due to statistical sampling cannot be reduced. Further, by basing performance on observations of operator detections and losses, the evaluation team loses any insight into whether the performance is influenced by environmental conditions.

Defining the Sensor Detection Footprint

The sensor detection footprint is the locus of points within the figure-of-merit (FOM) detection range of the sensor. It is similar to the FOM detection range but differs in that the variability in bearing of the noise and transmission loss is considered so that the footprint is a function of bearing. Because the footprint also takes temporal variations in the environment into account, it is also a function of time. One can think of the footprint as a graph, in polar coordinates, of detection range (radial coordinate) versus bearing (angle coordinate).

Estimating Footprints

A combination of models and real data is used in estimating the footprint. The footprint boundary solves the sonar equation

$$0 = SL - TL(\theta) - SG - BN(\theta, t) - RD \ ,$$

where

SL = target source level,
$TL(\theta)$ = acoustic transmission loss from the target to the sensor,
SG = sonar signal gain,
$BN(\theta, t)$ = sonar beam noise, and
RD = sonar recognition differential.

Each term above is estimated by data or modeling. Measured data are used whenever possible; when not available, Navy standard models are used. When possible, measurements of the target source level are obtained during the test and those values are used, especially for footprint validation (see the next section.) Once the footprint has been validated, other source levels can be used to assess how well the sonar will work against targets that are quieter or louder than the test target.

Transmission loss (*TL*) measurements can be made but are generally not part of an operational test. In some cases, a technical evaluation of the sonar in the same area that includes *TL* measurements may have already been done. If available, measured *TL* data are used; otherwise Navy standard models and databases are used to estimate *TL*.

Another key part of the footprint calculation is the measured beam noise at the output of the sonar beamformer. This is a unique part of the footprint estimate and differs from the standard approach of measuring the ambient noise and applying the theoretical array gain. The beam noise is the noise through which the target must be detected. It has all of the azimuthal and temporal variations of the ambient noise and clutter. It does not require any guesswork about the ambient noise directionality or how the beamformer (in the case of adaptive beamforming) interacts with the environment.

Several values can be used for the sonar recognition differential (*RD*). These values are generally accepted within the submarine towed array and surveillance communities for various kinds of signals and signal processing and represent the *RD* of an alerted sonar operator. During footprint validation, adjustments to the value of the *RD* are made to more accurately represent what the operators did during the test. *RD* can also be set to represent the best possible *RD* with the sonar system, regardless of how good the operator is at recognizing the signal on the sonar display.

Validating Footprints

Special care is taken to ensure that the calculated footprints are accurate representations of the areas in which detection occurs. This is accomplished using controlled test runs to reduce uncertainty in the terms in the sonar equation. Verification is made that the sonar gains the target at the same time it enters the footprint and that the sonar loses the target at the same time it exits the footprint. Keep in mind that the footprint is not used to make detections; it is simply a representation of sonar performance.

Once the accuracy of the footprints is verified, they can be used for further analysis. Figure 2 shows a qualitative comparison of the acoustic FOM footprints with sonar performance. The bearing versus time display on the left is similar to those commonly used on many sonar systems. The test target becomes visible at about minute 40 and is the trace that moves from left to right during

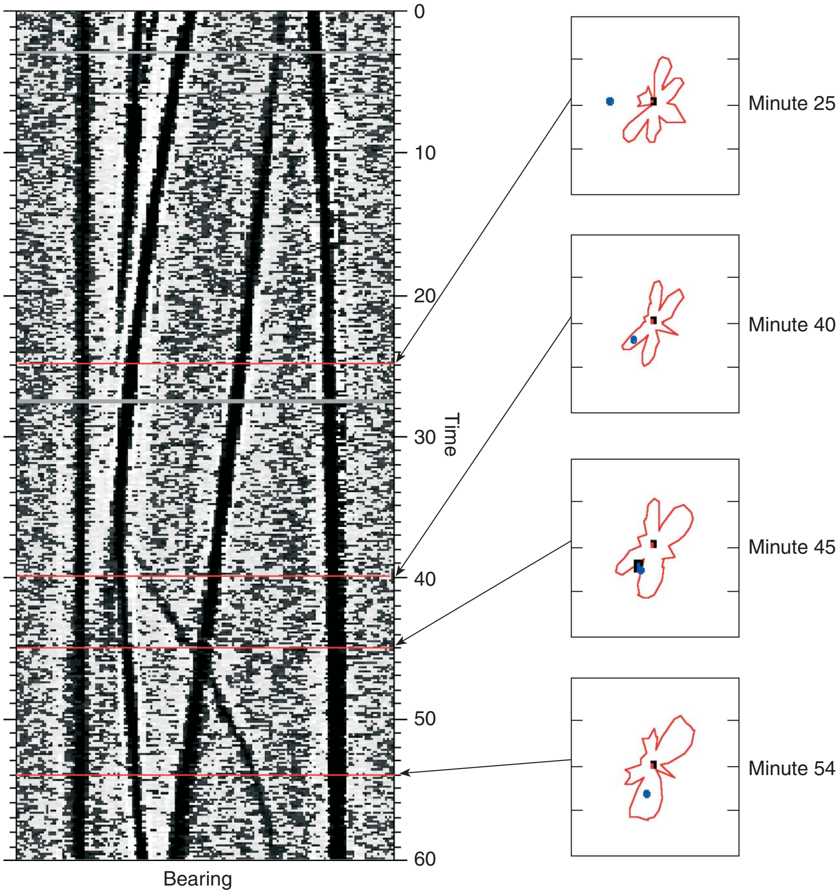


Figure 2. Example comparison of footprints (right) with a sonar display (left).

the last 20 minutes of the test time. The right side of the figure shows the footprint computed at different times during the test run. The red outline is the footprint, i.e., a plot of FOM range versus bearing. It varies with time because the ambient noise directionality, and hence the beam noise, varies. The blue dot indicates the position of the target (from navigation reconstruction) relative to the sonar receiver. Note that when the target is visible on the sonar display, it is inside the footprint. This comparison is a good qualitative verification that the footprints accurately represent sonar performance.

A quantitative verification can be done by computing the signal excess (*SE*) as follows:

$$SE = SL - TL(\theta) - SG - BN(\theta, t) - RD \ .$$

Figure 3 shows a comparison of the signal excess with a bearing versus time display that is similar to what a sonar operator uses. The signal excess was computed post-analysis using the source level for the target test ship and, at each time slice, using noise from the beam that points along the sensor to the target bearing as well as the *TL* (from a model) that was computed along the sensor-to-target bearing. This bearing was determined from navigation reconstruction and changes as a function of time.

At the beginning of the test run in Fig. 3 (bottom of the plots), the test ship is not observable on the sonar display (left), and the computed signal excess is a negative number. Just prior to minute 30, the test ship is barely observable on the sonar display, and the signal excess crosses over from negative to positive. In the latter part of the test run, the target is clearly visible and the signal excess is high. This quantitative comparison provides verification that terms in the sonar equation are correctly accounted for. Reliable footprints can be computed with the sonar equation by setting $SE = 0$.

In the examples shown in Figs. 2 and 3, agreement between target holding predicted by the footprint calculation and holding on the display is verified. The *RD* may be adjusted to cause this agreement (assuming there are no biases in other parts of the equation), and then that *RD* can be used to assess how well the sonar system works at making targets visible to the operator. This is called the system *RD*. During testing, the operator logs when he gained and lost the test ship and adjustments can be made to the *RD* accordingly. This is the operator *RD*.

The operator *RD* and system *RD* differ in that various factors can cause the operator *RD* to be higher (worse) than the system *RD*. These factors include operator training, alertness, fatigue, and whether the operator was actually looking at the display when the target first appeared. Having the two *RD* values allows us to use footprint calculations to assess the performance of the machine (sensor, signal processing, and displays) only, versus the machine and operator combination.

APPLICATION TO FIELDS AND TOWED ARRAYS

Sonar testing usually involves several days at sea, but a test target platform (with known source levels) is involved on only a few of those days. The footprints are validated with the test target platform. Footprints from the entire sea test, using beam noise data from the test, can then be used to assess the variation in the performance of the system over several days. This cannot be done within the limited time that a test target is available.

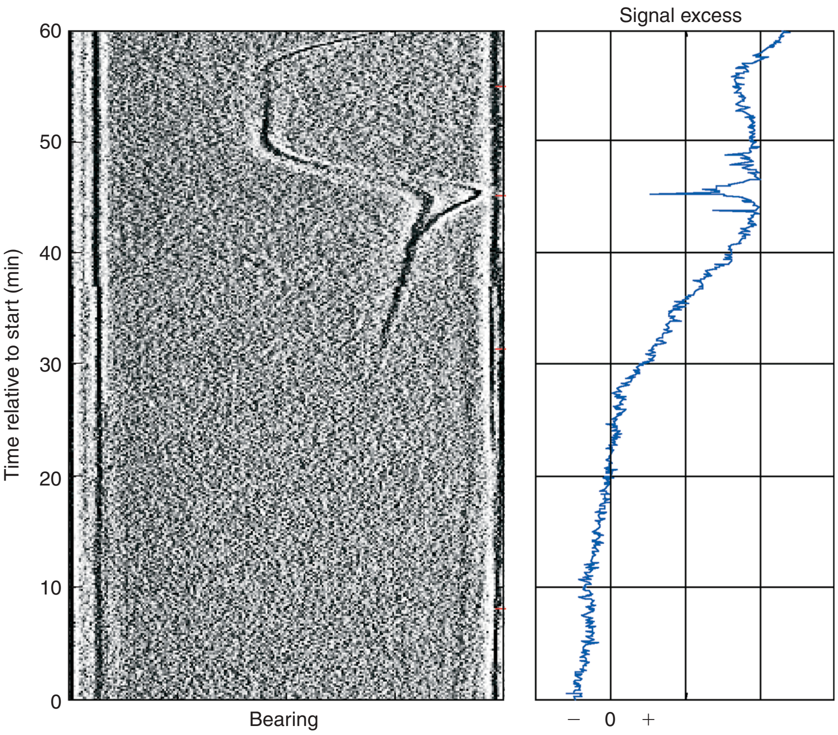


Figure 3. Example comparison of the signal excess (right) with a sonar display (left).

The Advanced Deployable System (ADS) is a distributed field of arrays currently being developed by SPAWAR PMW-183 to assess performance using a build-test-build methodology. During a recent test of an ADS field, beam noise data were collected from all arrays over a period of several weeks. In addition, towed sources were used to measure transmission loss around several of the arrays. The measured *TL* was compared with modeled *TL* (using a Navy standard model and databases) to validate the model. The model was used to make a complete map of the *TL* around each array.

Several target platforms were available, and special runs were designed to measure their source levels. The targets then operated under normal conditions in free-play mode, and target gains and losses were recorded. The footprints were computed for the free-play times, and the *RD* used in the calculations was adjusted so that the footprint gain and loss times matched the operator gain and loss times. This gave us the operator *RD*. In post-test analysis, the *RD* was adjusted so that the footprint gain and loss times matched the gain and loss times on the sonar displays. This gave us the system *RD*. Then the source level in the footprint calculations was changed to the source level specified in the ADS ORD. This enabled generation of the expected detection capability against the ADS ORD target in the region without an actual ORD target. Beam noise from several weeks of test time was utilized to assess how the ADS would perform over a long period.

A sample time slice of the footprints is shown in Fig. 4. Also shown are two of the test platforms and their tracks from the previous few minutes. This was done in post-test analysis with the reconstructed navigation. When this sample was taken, 14 arrays were operating. Only 12 footprints can be observed. Two of the arrays had very high ambient noise levels (due to nearby ships) and were not making detections. Other arrays had quiet ambient noise levels and very large footprints, sometimes overlapping footprints from other arrays. This picture changes rapidly in littoral environments and can often be completely different within an hour, with loud areas becoming quiet and vice versa.

The beam noise data were used to compute footprints at 5-min intervals for several weeks. This allowed observation of the variability in field coverage and assessment of how parameters like weather and shipping variations affect field performance. The footprints were further used to determine such metrics as field probability of detection (probability of detecting a patrolling target in the field in a given period of time) and mean time between target redetection. These metrics and variations could be explained in terms of observable environmental factors such as changes in shipping densities and weather.

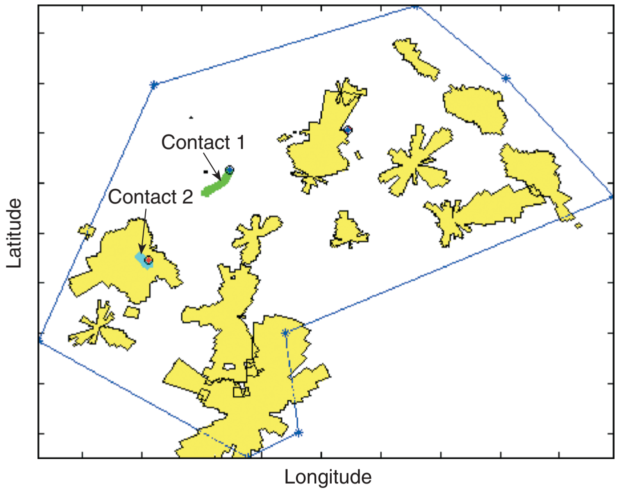


Figure 4. Footprints for a single time in a test of a field of ADS arrays.

Similar techniques have been applied to towed array data. Footprints were computed in the same manner described above: beam noise was collected at 5-min intervals to assess footprint variability, and test data were used to derive *RD* values for the operator and system. This technique was used to analyze a test of ARCI processing of a towed array.

The measure of performance that was of interest in testing this array was the sweep rate, that is, the amount of area (of the ocean) that can be searched in a given time period, usually specified in units of area/time. A direct measurement of the sweep rate can be made with the footprints. Figure 5 gives an example. It displays the tow ship, its track, and the latest footprint as well as the envelope of footprints from the previous hour. The example is shown for a period when there was a test target platform in the test, and this track is also indicated. The test target was used for footprint validation. The envelopes of the footprints from the previous hour define the area that was swept in the previous hour to produce an estimate of the sweep rate for that hour. Footprints were computed from several hours of data to assess the sweep rate and how it varied with time.

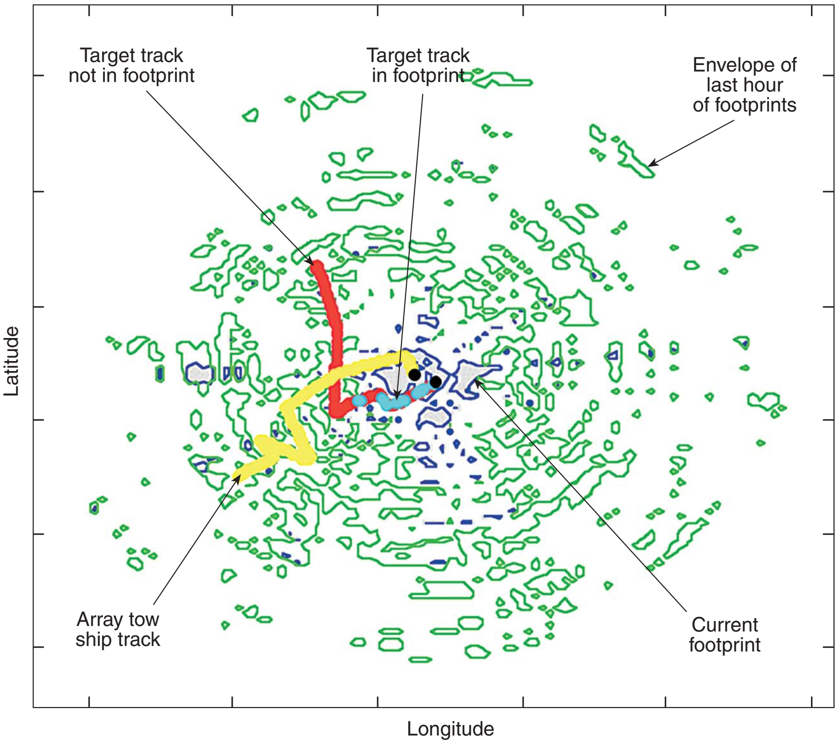
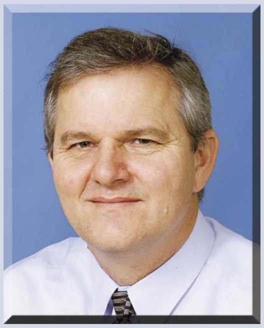


Figure 5. Footprint data showing 1 h of history.

CONCLUSION

Operational evaluation has evolved in response to changes in sonar system development and procurement. Although the new testing approach presented here requires commitment by the government sponsor in terms of labor and equipment, future funding decisions should be aided by an accurate view of current capabilities. Ground truth acoustic analysis performed post-exercise allows a true measurement of what sources from the test target are available to the operator and provides insight into possible areas for improved detection performance. The use of acoustic footprints allows the tester and system developer to understand why a sensor is not providing signal excess to the operator. Early teaming of the government testers, R&D laboratories, and the acquisition community brings an earlier understanding of possible problems, fosters trust between tester and developer, and ensures that the warfighter is receiving a system that not only meets current operational needs but can continue to evolve with the threat.

THE AUTHORS



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