Simulation of Active Sonar Bottom Clutter for Fleet Trainers

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ABSTRACT

In response to a critical Navy need for improved simulation in active sonar trainers, techniques for simulating ocean bottom clutter were developed at the Johns Hopkins University Applied Physics Laboratory (APL). The algorithm versions passed independent evaluation and were transitioned to the Navy's trainer implementation teams. The first version of the algorithm was designed for the Navy surface ship 53C sonar system and transitioned as part of the Advanced Capability Build 2011 (ACB-11). APL worked closely with the implementation contractor to ensure that the simulation output was sufficiently realistic to provide useful training. Upgrades were provided for ACB-13 in 2012. A third version of the algorithm was designed for the Navy's Naval Air Systems Command sonar system simulation Common Acoustic Synthetic Environment (CASE). This includes both the Multistatic Active Coherent and the Airborne Low-Frequency Sonar systems. APL worked closely with the CASE implementation contractor and participated in the acceptance testing by Navy operators. The operators rated the results as sufficiently realistic. A final revision of the algorithm was successfully evaluated independently and readied for transition to ACB-15.

BACKGROUND AND HISTORY

The U.S. Navy relies on active sonar to locate the quietest submarines of its potential adversaries. In active sonar for anti-submarine warfare, a loud pulse is transmitted, propagates through the ocean, reflects off the submarine hull, and returns to a receiver. In recent years, increasing environmental concerns about the effects of loud underwater sounds have led to restrictions and an increasing desire to limit active sonar operations. This reduction of operations negatively impacts the training of Navy sonar operators. Active sonar requires significant expertise to distinguish the desired signals from many sources of confusion. To make up for the limited use of real active sonar systems, the Navy is increasing its reliance on simulations to augment operator training. However, any simulation must be sufficiently realistic to provide useful training.

A study[1] in 2008 compared candidate synthetic sonar trainers and rated their realism. It was found that bottom clutter was the least realistic aspect of the existing trainers. In sonar parlance, *clutter* usually refers to those discrete echoes from unwanted objects that can be mistaken for the desired signals, as distinguished from more extended reverberation. The ocean bottom is generally the most significant source of sonar clutter and may contain gas pockets, embedded objects, rocky facets, and rough sediment surfaces that produce submarine-like echoes. Bottom clutter is generally more intense in areas with bathymetric features such as seamounts and undersea ridges. The existing trainers had unrealistically weak, sparse clutter. This made it too easy for trainees to identify desired signals and did not prepare them for the difficulties of real sonar system clutter. In addition, the clutter was equally likely to appear anywhere, and it was not associated with bathymetry, failing to provide a major classification clue for bottom clutter.

Partly motivated by the 2008 study, the Johns Hopkins University Applied Physics Laboratory (APL) undertook an independent research and development effort in FY2009 to improve the characterization of sonar bottom clutter. In particular, the focus was on simulating clutter that was a function of the location and depended on the underwater bathymetry. Also in FY2009, the Office of Naval Research (ONR) started a Fleet Naval Capability program for High-Fidelity Active Sonar Training (HiFAST). The hypothesis of HiFAST was that improving the physical realism behind the simulation effects would improve the realism of the simulation and thereby improve the training value. Many organizations received HiFAST funding to improve different aspects of active sonar simulation physics. APL joined the HiFAST program in FY2010.

INITIAL ALGORITHM DEVELOPMENTS

In FY2010, APL received funding from the Naval Sea Systems Command Program Executive Office for Integrated Warfare Systems to improve the bottom clutter in the surface ship 53C sonar simulation. APL rapidly developed an algorithm that gave increased clutter in regions of high bathymetric slopes. The algorithm was incorporated into the Advanced Capability Build 2011 (ACB-11). The ACB program uses a build–test–build philosophy that promotes rapid transitions of software improvements into Navy surface ship sonar processing and training systems. Later, an improved algorithm provided clutter that increased gradually as a function of increasing bathymetry slope. Regions with higher bottom slopes facing toward the sonar system displayed stronger, denser clutter. The improved algorithm was developed under ONR HiFAST funding and transitioned to Navy Fleet use in ACB-13.

It was clear from the beginning that a deterministic prediction of every piece of bottom clutter in the exact location and at the precise level of any real sonar transmission would not be achievable. However, a stochastic model that simulated random clutter that had realistic statistical properties might be possible and should be sufficient for training. A physical model of acoustic interaction with the rough ocean bottom interface based on perturbation theory was available;[2] however, this model had two limitations to its practical use. First, the model would only predict clutter from the rough interface and would not include contributions from sub-bottom inhomogeneities. Second, perturbation theory required a number of physical bottom parameters. Properties such as sediment density and sound speed were available in a standard Navy database, but the model also required the interface roughness at the Bragg wavenumber. The Bragg roughness has a length scale that is about half the acoustic wavelength, ~0.5–1.5 m for the Navy systems being considered. To use the model to simulate random clutter, the distribution of interface roughness would be required. The mean roughness alone would not be sufficient, but even mean roughness was rarely measured with sufficiently fine resolution, and no ocean-wide bottom roughness database exists.

An initial examination of bottom roughness data was undertaken to see whether a simple procedure could be found to supply the appropriate values to the perturbation model. Fine-scale measurements of ocean bottom roughness were obtained from several sites and processed. Roughness is typically characterized by a wavenumber spectrum, which describes the amplitude of roughness as a function of its length scale. It had been well known for years that the mean ocean bottom roughness (like land surface elevation) usually displayed a power-law wavenumber spectrum.[3] This was confirmed by the data available. However, the slopes of the power law varied across the sites, and the spectral levels varied by a few orders of magnitude. Thus, no single wavenumber spectrum could be used to predict the fine-scale roughness needed by perturbation theory from larger-scale bathymetry databases.

In addition to the mean ocean bottom roughness, the distribution of the roughness spectrum at the Bragg wavenumber was estimated from the data available. The distribution describes the probability of encountering roughness with any given level and requires accumulation of values over a large number of independent subareas within a site. One example of the bottom roughness data examined is from the ONR "Geoclutter" site off the coast of New Jersey and is shown in Fig. 1. The plot shows the probability of exceeding a given spectral power level. This is also known as the complementary cumulative distribution, which is 1 minus the cumulative probability distribution. Using this format on a logarithmic scale allows the detail of the upper tail of the distribution to be closely examined. The upper tail (in the lower right of the plot) characterizes the highest-level deviations above the mean, which are the values that behave as false target clutter. The upper tail of the data (blue curve) approaches a straight line indicating a power law. Notice that the blue data curve is mostly hidden behind the red generalized Pareto power-law curve, showing the appropriateness of that model. The upper tail clearly deviates

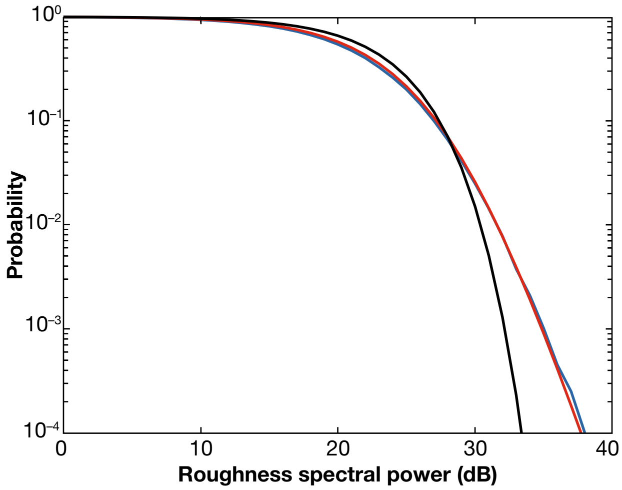

Figure 1. Distribution of fine-scale bottom roughness at the Geoclutter site compared with model distribution functions. The blue curve is data, the red curve is generalized Pareto distribution, and the black curve is exponential distribution.

well above the exponential distribution (black curve in Fig. 1) that would be appropriate if the underlying data were Gaussian. Thus, there are many more extremely rough patches present than one might expect from the standard Gaussian assumption.

In perturbation theory, acoustic scattering is linearly proportional to interface roughness. Thus, perturbation theory implies that the distribution of acoustic scattering from power-law distributed rough surfaces should also have a power-law distribution. Other researchers[4] had observed power-law distributions of ocean clutter, and this was confirmed by our own examination of acoustic clutter data, as shown in Fig. 2. Note that a power law is a much heavier tailed distribution than would be obtained from a normal distribution, so clearly the often assumed central limit theorem does not usually apply to ocean bottom clutter. The k distribution[5] is a heavy-tailed distribution that has often been applied to radar and sonar clutter. However, the k distribution (magenta curve in Fig. 2) does not have a power-law upper tail, and it is not sufficiently heavy for the data we examined, falling well below the data confidence bounds shown by the cyan curves. The generalized Pareto distribution with a power-law upper tail (red) characterized these data (dark blue in Fig. 2) much better.

APL developed a semiempirical model to simulate ocean bottom clutter—motivated by perturbation theory and the observations of bottom roughness and clutter described in the preceding paragraphs. First, the existing simulators already predicted the mean level of ocean bottom reverberation. These predictions incorporated physical models for the ensonification of the ocean bottom and the grazing angle dependence of acoustic scattering. The semiempirical clutter model assumed that the clutter distribution had this same mean level. APL has experience using a generalized gamma distribution to characterize passive sonar shipping noise levels, which can be thought of as clutter for passive sonar. It was also known that for some parameter values, the generalized gamma distribution has a power-law upper tail. Hence, the generalized gamma distribution was initially chosen to characterize the active bottom clutter. Later efforts[6] showed that an even better match was obtained with the generalized Pareto distribution, which is shown in Figs. 1 and 2. Because ocean roughness values were not generally available, we used bathymetric slope as a surrogate for roughness. In many instances, flatter ocean bottoms are composed of smooth sediment layers, while steeper sections of seamounts and ridges can have rougher exposed rocky outcrops. The distribution parameters depended on slope—specifically the bathymetry gradient in the sonar direction—to produce a heavier tail distribution for steep slopes facing toward the sonar system. We draw random clutter points from a different distribution within each bathymetry cell of the database.

In FY2010, APL handed the initial algorithm description over to the implementation organization for ACB-11, SAIC (Science Applications International Corporation). During FY2010–2011, SAIC implemented the algorithms in the real-time simulation system and generated sample displays. The initial displays were improved but still somewhat lacking in realism. Some implementation details were different than expected, for example, to take advantage of existing code. Furthermore, sonar displays involve nonlinear normalizers and nonuniform display quan-

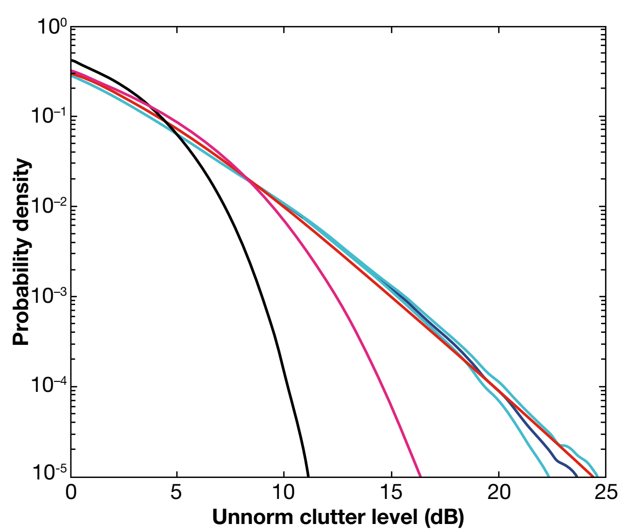

Figure 2. Distribution of acoustic clutter levels from North Atlantic Treaty Organization (NATO) exercise BASE 04 experiment. Blue is data distribution with cyan 99% confidence bounds. The red curve is generalized Pareto distribution, magenta is best-fit k distribution, and black is exponential distribution.

tization levels, making the display appearance difficult to predict. However, by this time APL had considerable experience with the effects of the clutter distribution parameters and made adjustments to the initial parameter settings. This produced displays that were considerably more realistic than previously available, and they were acceptable for incorporation in the Fleet system ACB-11 upgrade.

The initial ACB-11 algorithm used one heavy-tailed generalized gamma distribution in regions of high slope and the default Rayleigh distribution elsewhere. It was recognized during testing that a more gradual transition between regions would be more physically realistic. A new algorithm version varied the generalized gamma shape parameters gradually to provide transitions from near-Rayleigh flat areas to much heavier tailed behavior in the steepest areas. This new version passed an independent evaluation and was transitioned to ACB-13.

VERSION FOR NAVAL AIR SYSTEMS COMMAND SYSTEMS

The Navy also deploys active sonar systems from aircraft and uses the Common Acoustic Synthetic Environment (CASE) tool to simulate and provide training for them. The CASE system must run on the more limited computational hardware available for air systems Fleet training. Furthermore, the system must be capable of handling multi-static systems, such as the Multi-static Active Coherent (MAC) system, which use a large number of sources and receivers simultaneously. The legacy CASE clutter simulator injected a few recorded samples of clutter into random locations. There was no correspondence with bathymetry. Furthermore, smart trainees might eventually learn to recognize the entire library of recorded clutter samples. Under the HiFAST program, APL responded to the need to provide a more physical basis for ocean bottom clutter to improve training complexity and to maintain bottom clutter realism without increasing the computational load. We also minimized the implementation differences from the legacy system.

The concept was to replace the recorded clutter samples with clutter objects that varied randomly in size, level, and spatial density. The objects were more densely populated in regions with higher bathymetric slope, and as with the ACB approach, the objects also had heavier-tailed distribution parameters with higher slopes. For each bistatic MAC source–receiver pair, the slope was characterized by the bathymetry gradient in the bistatic angle direction (i.e., the bisector of the source and receiver angles). The ONR HiFAST program adapted the multistep evaluation process developed by the Advanced Processor Build program. The first step is peer review of the theory and results by a committee of experts. The second step involves handing the algorithm over to an independent evaluation organization for detailed comparison with data. In this case, the Applied Research Laboratories of the University of Texas at Austin (ARL:UT) conducted the step 2 evaluation in FY2012. To support the evaluation, APL implemented the bottom clutter algorithm in the Sonar Simulation Toolset, a simulation tool[7] developed by the Applied Physics Laboratory at the University of Washington. APL ran a large set of simulations in locations selected by ARL:UT, and ARL:UT performed detailed statistical comparisons between the Sonar Simulation Toolset outputs and data recorded at the same locations. The evaluation data set was closed to APL (i.e., we could not adjust parameters in advance to match data). The bottom clutter algorithm was one of only two out of many HiFAST components that successfully passed step 2, and the algorithm description was provided to the CASE implementer, Advanced Acoustic Concepts, LLC.

In FY2013, APL worked closely with Advanced Acoustic Concepts to ensure appropriate implementation and to refine parameters. The implementation was soon ready for final testing—a step 3 evaluation in which trained Navy sonar operator experts compared the simulation results with recorded data playbacks from both MAC and Airborne Low-Frequency Sonar systems provided by the Navy. The operators were generally very pleased with the simulation and rated it sufficiently realistic for positive training. Step 3 was passed, and the algorithm became part of CASE release version 19.3 for Fleet use. The rating would have been higher, but one Airborne Low-Frequency Sonar data collection showed clutter apparently from a small bathymetric ridge that was not reproduced in the simulation. A close examination of the bathymetry database during the testing showed no ridge at this location, so naturally the simulation could not reproduce the ridge effect. A few weeks later, it was discovered that the data collection location had been erroneously documented by the Navy. The simulation was rerun in the correct location, and the ridge clutter effects were apparent and realistic.

ALGORITHM REFINEMENT

While the CASE improvements were being implemented in FY2013, APL returned its attention to the 53C sonar and further improvements to the model's realism. Continuing under ONR HiFAST funding, APL had an opportunity to provide improvements to the next simulation software build, ACB-15. Previous work[6] had shown that clutter data were better characterized by a generalized Pareto distribution than by the generalized gamma distribution used in the ACB-13 version. This improved distribution would allow more high-level clutter without causing an unrealistically overwhelming amount of low-level clutter.

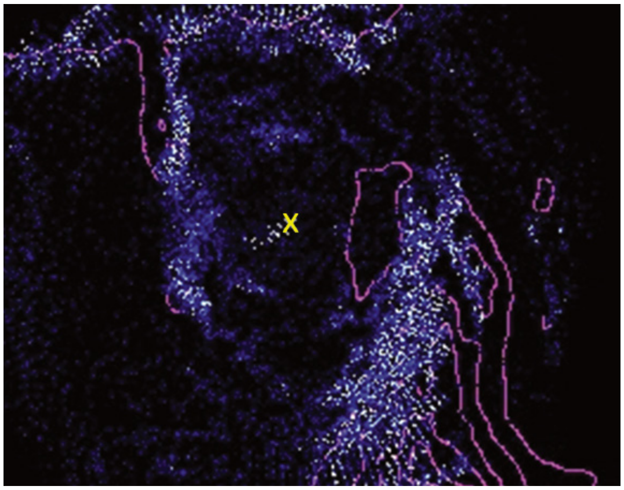

Figure 3. A portion of a simulated sonar display, with bathymetry contour overlay.

In addition, we considered the Navy's sediment-type database as another surrogate for bottom roughness and resulting bottom clutter. Clearly, one expects rocky areas to be rougher than areas with silt, mud, or clay bottoms. The sediment database has some limitations, primarily in being based on the limited data available. Often large areas are shown as being clay—even steep slopes of seamounts where that is physically unlikely. Nonetheless, whenever the sediment-type database shows the presence of rocks, cobbles, or coarse sand, one should expect potential for increased roughness and clutter. A new empirical roughness estimator was developed that combined the previous bathymetric slope predictions with sediment type-predictions. The bottom clutter distribution upper tail parameter was now heavier both in regions of high slope and in regions with coarser sediment types. This new version also passed ONR's independent step 2 testing, and algorithm description documentation and software were transitioned to the ACB implementation team.

A sample simulated sonar display is shown in Fig. 3. The ocean bottom elevation (bathymetry) contour lines are overlaid on the display. The location is off the coast of Southern California, between two submerged ridges. The sonar system is located at the central point indicated by a yellow X. Notice that the bottom clutter is more concentrated along the sides of the ridges facing the sonar system.

SUMMARY

Algorithms to realistically simulate active sonar clutter from the ocean bottom were rapidly developed for use in Fleet sonar trainers. Although the algorithms were motivated by physical models, they involved semiempirical choices of stochastic distribution parameters to achieve a realistic appearance. Versions of the algorithms passed independent testing and were successfully integrated into the ACB-11 and ACB-13 (simulating surface ship systems) and CASE 19.3 (simulating air-deployed systems) Fleet trainers.

ACKNOWLEDGMENTS: Other members of the APL team were Fred Newman, Juan Arvelo, and Will Sweeney, all of whom made significant contributions to the effort's success. Brian La Cour of ARL:UT and Bob Goddard of the Applied Physics Laboratory at the University of Washington provided assistance in implementing a Sonar Simulation Toolset version to prepare for step 2 testing.

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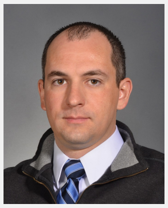

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