An Innovative Radar Clutter Model

By George LeFurjah

Engineers at the Naval Surface Warfare Center (NSWC) Dahlgren have pioneered a new method for modeling the complex environments that our Navy and Marine Corps face when operating radar systems throughout the world. The innovation involves combining radar clutter and atmospheric ducting models, including state-of-the-art meteorological modeling. This is a groundbreaking effort—the first of its kind anywhere. The result is the Littoral Clutter Model (LCM). Although originally intended strictly as a model for shipboard radars, LCM has been extended to also apply to land-based radar applications. This article describes this new model and shows how it can be used to enhance Navy target detection, tracking, and discrimination capabilities in littoral environments.

Background – Complex Environments

There are two aspects to what is meant by environment: objects that are in the field of view of the radar and the atmospheric conditions that affect how those objects appear to the radar system. Radar operates by radiating electromagnetic energy from a focused antenna in the direction of some interesting targets; those targets are just a subset of the many objects in the radar's field of view. That energy, typically in the form of short bursts or pulses, is concentrated by the antenna into a relatively narrow part of that field of view. When the energy is reflected from an object, it rebounds in the direction of the radar antenna and is then received and processed by the radar. Atmospheric conditions affect the path of that energy in two ways. Energy is absorbed by the atmosphere, and the path is altered by atmospheric refraction and, to a lesser degree, diffraction around intervening objects. The absorption process reduces the amount of reflected energy that the radar can receive, making it a little harder to detect the targets. Refraction is the more troublesome of the effects. Simple refraction changes the apparent direction of the targets. When the atmosphere is sufficiently layered in temperature or humidity, a refractive layer can act to bend the path down to where the energy reflects back and forth between the surface and the layer. An analogy of this effect is the optical refraction that occurs when a person looks at a fish underwater. The layer, or the boundary between the water and the air, refracts the light, bending it such that the fish is on a different line to the eye than is apparent. If the person looks at a shallow enough angle, the surface no longer appears transparent, but rather it appears to be like a mirror. A similar refractive bending occurs in the atmosphere when the temperature, humidity, or air density forms layers. Under certain conditions, a layer above the radar can act as a partially reflective surface in which the pulse can be reflected back towards the surface, and by virtue of multiple reflections, the pulse can travel for great lengths along the surface. In the absence of such a condition, the pulse would travel in nearly a straight line and, because of the earth's curvature, diverge from the surface. A depiction of the atmospheric boundary layer is shown in Figure 1.

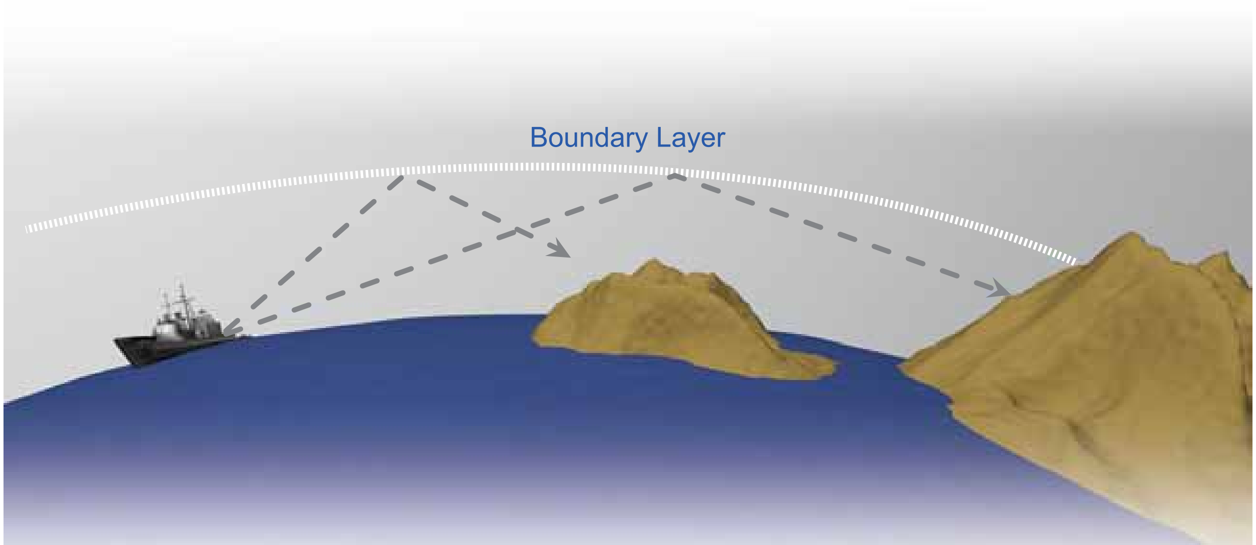


Figure 1. Atmospheric Boundary Layer

Because it is analogous to a waveguide, this condition is called atmospheric ducting, or simply ducting. This situation is not unique to radars. If you listen to radio in these conditions, you can sometimes pick up stations far away from your local area, sometimes hundreds of miles over the horizon from your location. The atmosphere does not have cut-and-dried simple layers, and the surface of the earth is not a flat, featureless plain. Thus, these complications make the prediction of how that path is altered a nontrivial exercise.

Clutter, simply put, represents targets that are of no interest to the radar's mission, which is typically to detect and track moving air or ground vehicles. Of course, one radar's clutter might be another radar's target. Weather radar, for example, tries to detect storm clouds and measure their velocity. Military radar would consider storm clouds to be clutter. Clutter is named for the appearance it presents on a typical radar display. Instead of simple target blips, the operator sees a scattered hash of signals. Some examples of clutter are rainstorms, sea surface scatter, land, trees, mountains, and buildings. Clutter has a number of undesirable effects on radar's operation. It obscures targets by overpowering the target's signal and is often simply a bigger target than a boat, aircraft, or missile. In other words, clutter reduces the ability to detect targets of interest. This is the probability of detection problem. The other key problem with clutter is that it can look like a target; it, too, can be detected and tracked. This is called the false alarm problem. When radar automatically detects and tracks targets, clutter can overload the system with false tracks. Once again, if it were weather radar, these storms tracks would not be false at all. Whatever the perspective as to what constitutes clutter, it is a problem for radar that must be acknowledged, accounted for, and dealt with.

When the atmosphere enhances propagation on the surface, then clutter—which is almost entirely a near surface phenomenon—can present returns from many miles, even hundreds of miles, away from the radar. This long-range and extended clutter is much more of a problem in both detection and false alarms. Figure 2 depicts recorded radar data from USS *Lake Erie* operating in the Persian Gulf. In this depiction, ducting conditions caused land clutter to be visible from hundreds of miles away. The radar is generating a picture of the whole shoreline of the Gulf, even inland in Iraq.

Littoral Radar Clutter Model

Coastal (or littoral) combat operations are the major drivers for current U.S. Navy radar system design. As we have seen, coping with clutter and atmospheric considerations is crucial to the task of providing adequate new radars. Consequently, adequate simulations of the environments faced by these new radars are crucial for radar system design and radar system performance analysis. In the current acquisition environment, adequate simulations are also a crucial adjunct to expensive, live system testing. When based upon complex spatially and temporally inhomogeneous atmospheric propagation prediction, realistic littoral clutter predictions are useful from all of these perspectives. When used in conjunction with radio frequency (RF) scene generation, these models can even replace some radar performance specification testing. All these considerations led to the development of LCM at NSWC Dahlgren.

LCM is a synthesis of several elementary models—a model of models (see Table 1). LCM models surface clutter from the land and the sea, while using up-to-date topographical data. It also models the atmosphere's effect by modeling the refractive properties of the atmosphere and the propagation of the radar pulse through that atmosphere using a mathematical process called parabolic equation computation. NSWC Dahlgren pioneered the use of mesoscale numerical weather prediction (MSNWP) technology to generate a 3-D picture of the atmospheric refraction.

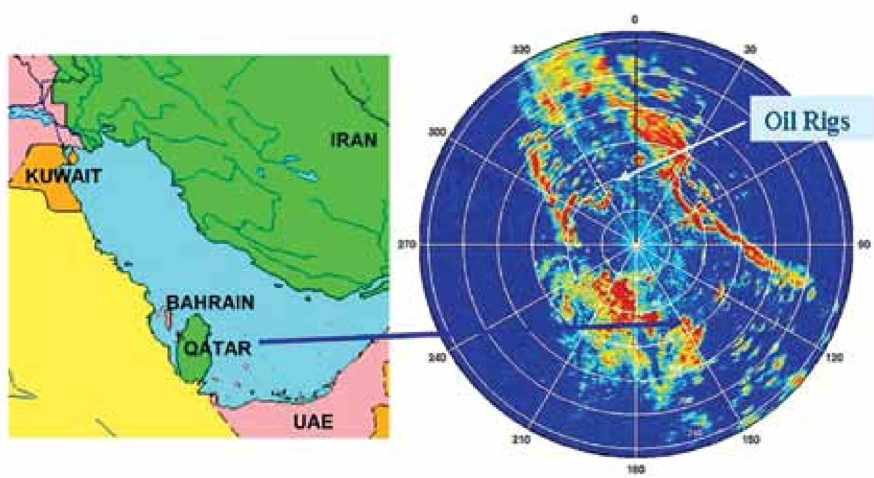


Figure 2. Map of Recorded Radar Data from the Persian Gulf with the Geographic Map of the Region

Table 1. Littoral Model Component Models

DTED Level 1 Terrain Data—to model Land Topography
AVHRR Global Land Cover Database—to model Land Surface Reflectivity Characteristics
Billingsley Empirical Land Clutter Model—for Land Radar Reflectivity (σ^0)
GTRI Sea Clutter Model—for Sea Surface Reflectivity (σ^0)
JHU/APL TEMPER Radar Propagation Model—to compute Propagation Factor (F^4)
COAMPS—Coupled Ocean/Atmosphere Mesoscale Prediction System to model the atmosphere

Component Model Descriptions

Input Data

Variable height, site-specific terrain, is computed with terrain contours from Digital Terrain Elevation Data (DTED) files provided by the National Geospatial-Intelligence Agency (NGA).

The United States Geological Survey (USGS) provides a global land cover database, Advanced Very High Resolution Radiometer (AVHRR), with 24 terrain type classifications with a latitude and longitude worldwide reference. The terrain types are correlated with the DTED data to associate appropriate electrical properties and surface roughness values with each patch of terrain. Together, these data provide the terrain heights, electrical properties, and surface roughness for each clutter patch along each radar propagation path. In addition, they provide inputs for the computation of clutter reflectivity.

Surface Clutter Models

LCM is primarily a statistical model, meaning that the clutter is computed based upon known statistical variations rather than on precise modeling of every object that might be in the radar field of view; but the statistics are computed based upon the nature of the surface on the earth at specific locations. In order to model backscatter from patches of terrain or ocean surface, it is usually necessary to employ an empirical clutter model, rather than a conceptual or physics-based clutter model. This is especially true in the case of low-angle radar clutter, where this model applies. The empirical models employed provided, distributed clutter amplitude statistics, in terms of Weibull means and spreads, to represent the normalized clutter reflectivity, σ^0. The radar cross section of a patch of surface clutter is computed as σ^0 times the propagation factor, multiplied by the area of the clutter cell. The Navy-Standard Georgia Tech Research Institute (GTRI) model provides σ^0 for sea clutter, and the low-angle radar empirical land clutter model designed by J. Barrie Billingsley at Massachusetts Institute of Technology (MIT) Lincoln Laboratory provides σ^0 for land clutter.

The Billingsley land clutter model was chosen for very low-angle radar land clutter. It is based upon extensive land clutter measurements conducted by MIT Lincoln Laboratory of a large range of terrain types over a range of depression angles and surface slopes, for both vertical and horizontal polarization, and from very high frequency (VHF) to X-band, approximately 200 MHz to 10 GHz.

Atmospheric Propagation Model

Parabolic equation computation provides a fast solution to Maxwell's equations. Although the details of this process are beyond the scope of this article, this technique allows the modeling of the atmospheric propagation over a realistic, topographically complicated surface. The atmospheric refractivity may vary with respect to range and height. The surface boundary may be ocean or variable height terrain of range-varying composition. The Tropospheric Electromagnetic Parabolic Equation Routine (TEMPER) is a parabolic equation code that was developed at the Johns Hopkins University Applied Physics Laboratory (JHU/APL). It uses refractivity profiles, which are refractivity as a function of height and ground location, as well as surface roughness derived from surface land cover to compute radar propagation.

Mesoscale Numerical Weather Prediction (MSNWP)

The weather reports we see on the news every night are predicated upon complex computer simulations of the atmosphere. These models cover very large areas of the earth and are called synoptic weather prediction models. MSNWP is a very similar process but computed for much smaller areas. To get an idea of the scope, synoptic models might cover thousands of miles; mesoscale models cover a few hundred. The idea of using MSNWP to generate realistic depictions of site-specific atmospheric conditions and combining them with site-specific clutter is a unique development innovated at NSWC Dahlgren.

MSNWP is the numerical modeling of the physical/dynamical nonlinear differential equations that govern atmospheric flow. Initial conditions are developed by combining previous forecasts with new meteorological observations through a process termed ***data assimilation***. Simultaneous numerical integration of these equations provides a prognostic capability out to 72 hours. MSNWP models are typically 100 × 100 km and nested within a global forecast model. The lateral boundary conditions for the MSNWP models are derived from the larger scale global model. MSNWP models employ horizontal grid resolutions sufficient to resolve circulations produced by local surface features, such as air/land/sea boundaries and topography. Advances in computing power allow for horizontal resolution as fine as 1 km. In order to provide this resolution over an area of interest, MSNWP models are multi-nested, with the resolution becoming finer from nested grid to the next nested grid. Resolving near-surface refractivity is one of the most challenging applications for MSNWP, where refractivity profiles are derived from the MSNWP model profiles of pressure, temperature, and humidity. Research and development classes of MSNWP models currently may provide 10 m vertical resolution in the first 100 m near the surface.

MSNWP currently provides a qualitative, four-dimensional—three spatial dimensions and time—refractivity field in the littorals. The MSNWP model will resolve the local circulation that produces the current anomalous propagation regime. The phase of the circulation, the height of the atmospheric boundary layer, the vertical gradients of temperature and water vapor, and the sea surface temperature will be slightly different from those measured by in situ meteorological instrumentation. This will result in some duct height and strength errors but will provide insight into the varying structure of coastal refractivity.

The Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) is the MSNWP model that has been chosen for use in LCM. It was developed by the Marine Meteorology Division of the Naval Research Laboratory (NRL) in Monterey, California.

Oil Rig Platform Clutter

Although the Billingsley statistical data (referenced in Table 1) does a good job of predicting the occasional large-amplitude return from land clutter, it will not predict the return from discrete objects that are permanently installed away from shore. The biggest of these in terms of reflecting radar energy are oil-drilling and ship-loading platforms. The Vector Vertical Obstruction Database (VVOD), developed and maintained by NGA, provides the locations of these oil rigs. By using this database and modeling the radar return from these rigs as analogous to a large ship, LCM has been modified to include a discrete clutter layer that reveals the radar return as an overlay on the basic LCM clutter picture. Figure 3 shows an example oil-drilling platform.

An Example Use of LCM

Figure 4 illustrates an example that shows the realistic portrayal of clutter possible with the LCM clutter simulation. For this example, the model was centered at the latitude and longitude coordinates of USS *Lake Erie* at the moment clutter was recorded. That data is shown in the Plan Position Indicator (PPI) display on the right side of the figure. The COAMPS weather prediction code was used to generate a prediction of the atmospheric conditions at the time of the data collection. The COAMPS data for this study were generated at the NSWC Dahlgren. As can be seen on the left side of the figure, the LCM-generated data is a very reasonable depiction of what was actually seen aboard ship. The shoreline, islands, inland mountains in Iran (to the top right of the PPIs) and the oil rigs are seen clearly in both pictures. Some of the details—such as low-level sea clutter near the ship—are missing from the model. Currently, engineers and meteorologists at NSWC Dahlgren and NRL Monterey are working on improvements to the resolution of COAMPS near the surface, which hopefully, will increase the accuracy of model results even more.

As a result of these innovative radar-clutter modeling efforts, Navy warfighters in the future will be better armed with enhanced target detection, tracking, and discrimination capabilities in littoral environments.

Figure 3. An Example Oil Drilling Platform

LCM with COAMPS

Clutter Data Recorded Aboard USS *Lake Erie*

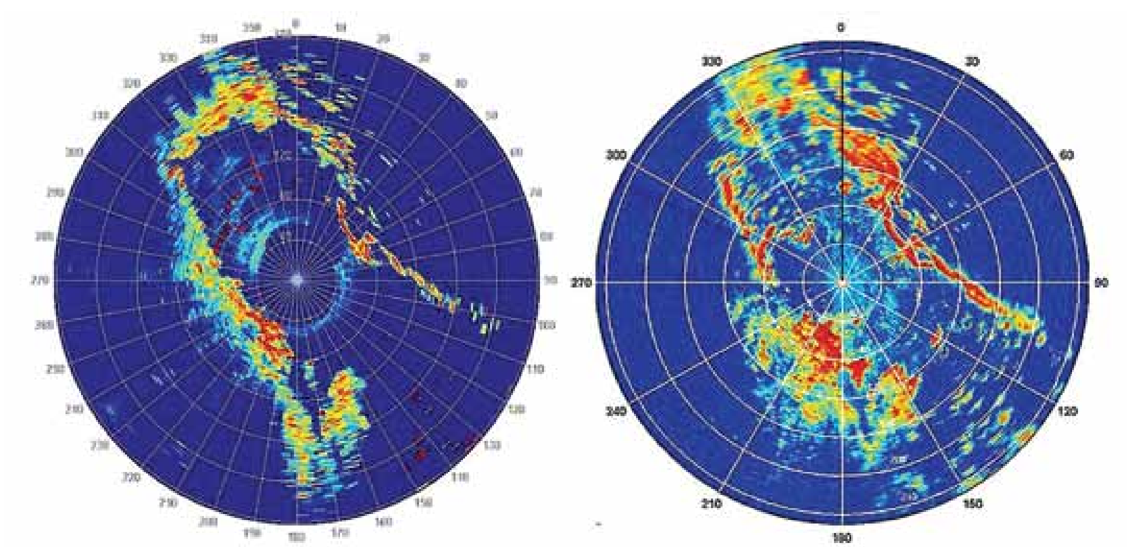
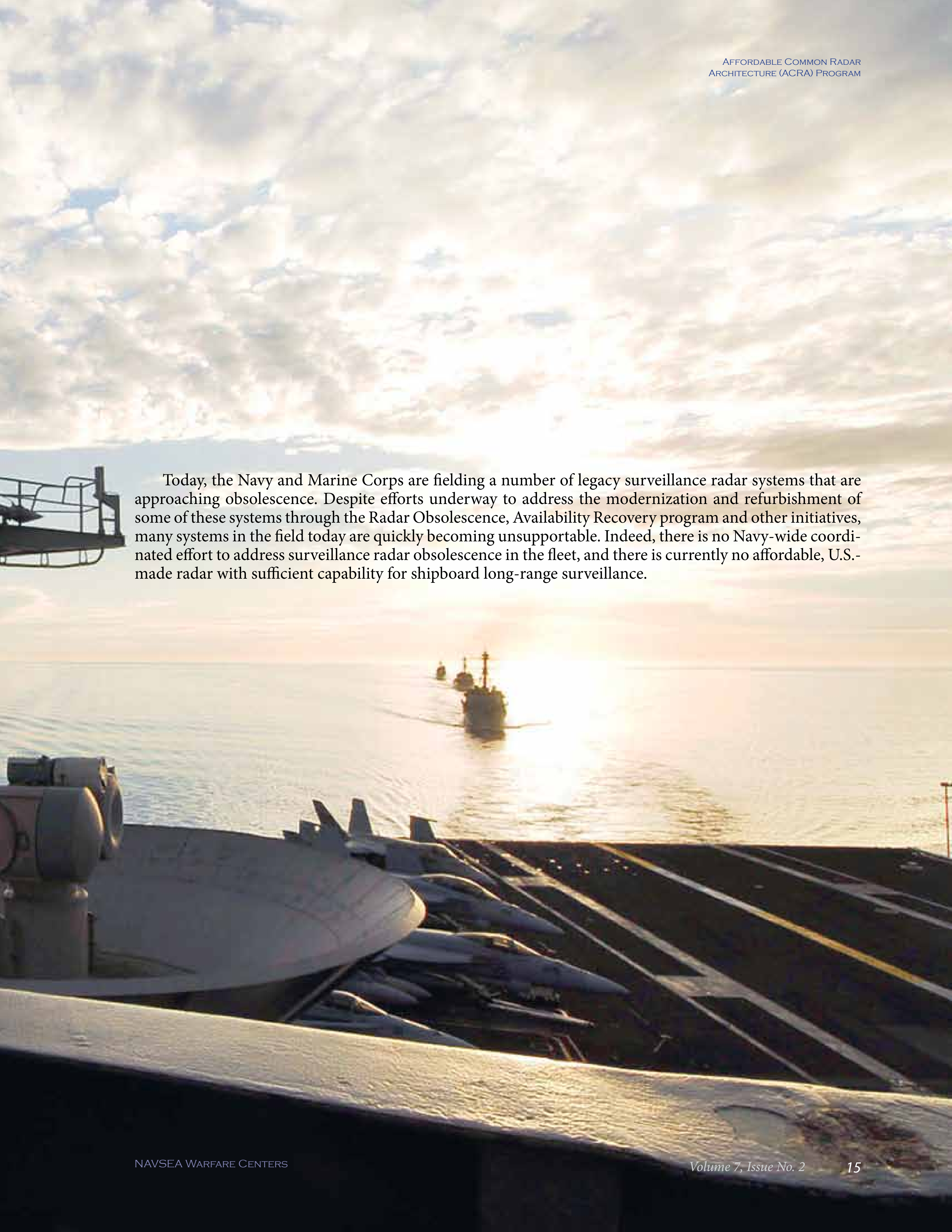


Figure 4. Littoral Clutter Model Simulation of Clutter Seen Aboard USS *Lake Erie*

Affordable Common Radar Architecture (ACRA) Program

By Stephen G. Thomas



Today, the Navy and Marine Corps are fielding a number of legacy surveillance radar systems that are approaching obsolescence. Despite efforts underway to address the modernization and refurbishment of some of these systems through the Radar Obsolescence, Availability Recovery program and other initiatives, many systems in the field today are quickly becoming unsupportable. Indeed, there is no Navy-wide coordinated effort to address surveillance radar obsolescence in the fleet, and there is currently no affordable, U.S.-made radar with sufficient capability for shipboard long-range surveillance.

Legacy surveillance radar systems approaching obsolescence include the AN/SPN-43, AN/SPS-48E, TPS-59(v)3, AN/TPS-75, and AN/SPS-49(V). They provide the fleet and the Marine Corps with a range of capabilities necessary for air traffic control and combat operations. Moreover, in addition to these systems approaching obsolescence, much of the current supply has been refurbished. Systems approaching obsolescence are shown in Figure 1.

In light of the need for timely and affordable system modernization across the board, the Office of Naval Research (ONR) initiated a Future Naval Capability (FNC)-funded program and tasked the Naval Surface Warfare Center, Dahlgren Division (NSWCDD) with oversight, technical direction, technology development, and integration. The Affordable Common Radar Architecture (ACRA) program, kicked off in FY09, is a risk-reduction effort with the goal of developing a scalable, common architecture with supporting technologies applicable to long-range surveillance radars. For the warfighter, ACRA represents improved performance in the littoral regions with a reliable, supportable, affordable system. The ACRA program will provide capability for both rotating phased arrays and multifaced fixed arrays based on a core group of common, scalable components. These

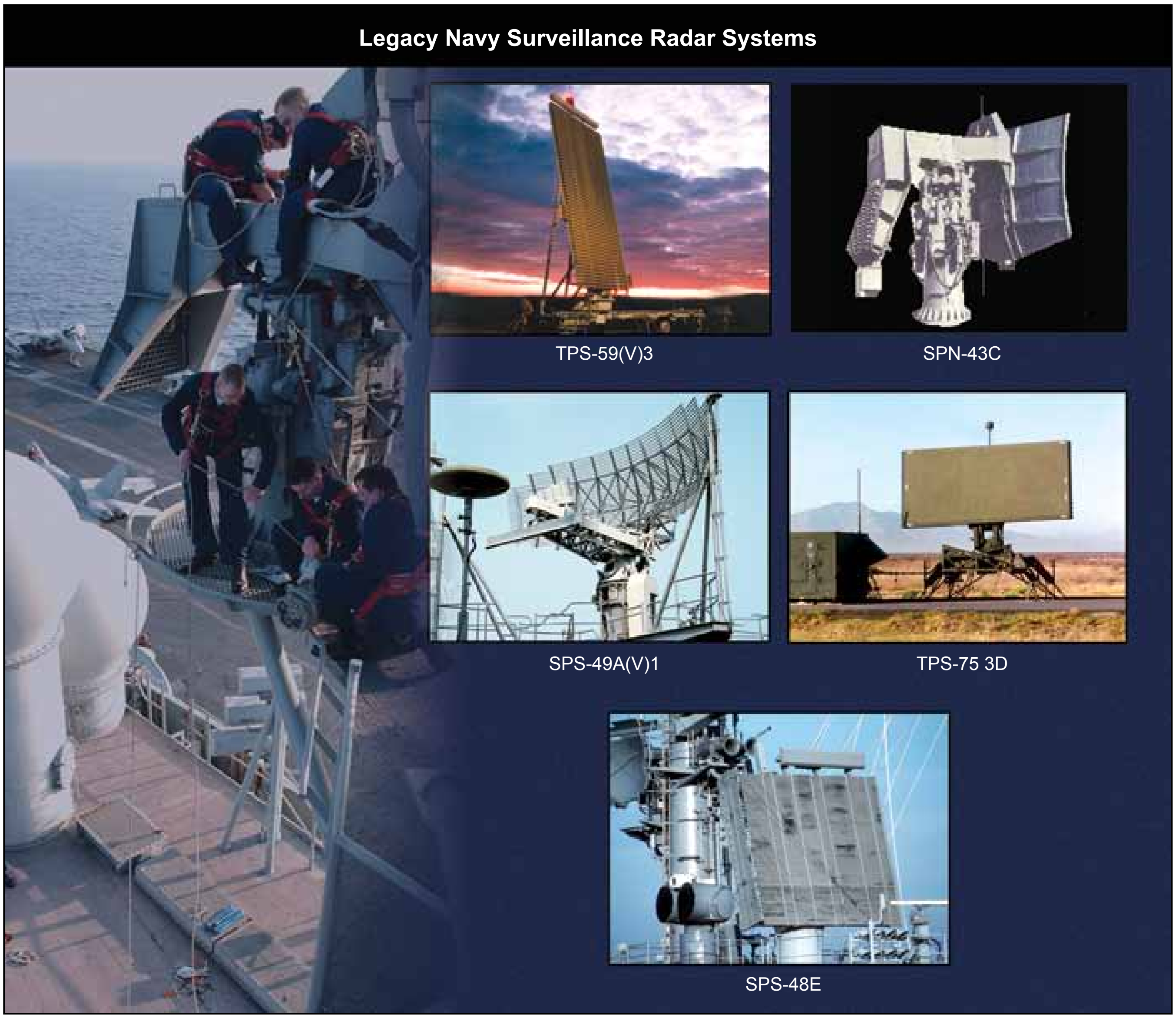


Figure 1. Legacy Surveillance Radar Systems Approaching Obsolescence

components include the radar array's mechanical structure and electrical signal network, digital receivers, waveform generators, and data processor. Separate transmit (TX) and receive (RX) arrays flood a search region with a single, wide TX beam and multiple, digitally formed, simultaneous RX beams. The digital receivers are located on the array structure, while the beamforming and TX circuitry is located below decks. Figure 2 shows a conceptual drawing of these components.

The 5-year program plan calls for the design and construction of an affordable Advanced Development Model (ADM) risk-reduction, rotating radar prototype. Unlike many current radar systems, the ACRA radar will comprise two separate antenna structures—a TX array and an RX array—in contrast to a single, common TX/RX array. This has the potential to lower overall system cost through a number of innovative array design techniques currently being investigated by NSWCDD and the ACRA team. For example, a low-power, air-cooled RX array printed circuit board design and a small, passive TX array are currently undergoing cost and performance trade studies. In parallel with array development, NSWCDD is involved in technology development efforts aimed at producing cost-effective, scalable receivers; waveform generators; and signal processors based on an open-architecture specification developed by NSWCDD for the ONR Digital Array Radar (DAR) program. Once the array and technology risk-reduction and development efforts are completed, the entire system will be integrated into an ADM prototype for testing and demonstration in FY13. These ACRA system components will leverage DAR technologies and cost-saving concepts. ACRA system components are shown in Figure 3.

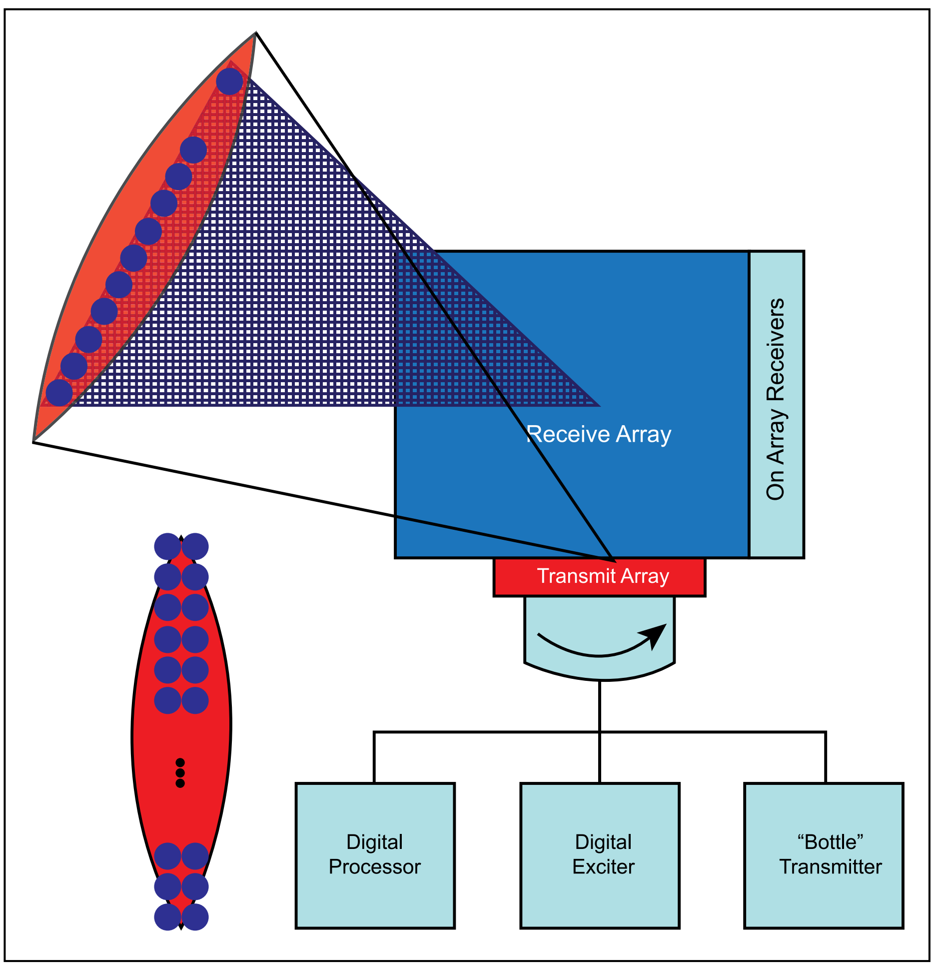
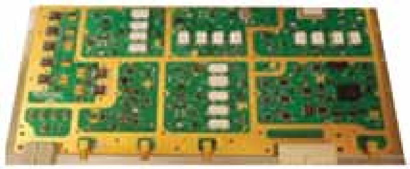
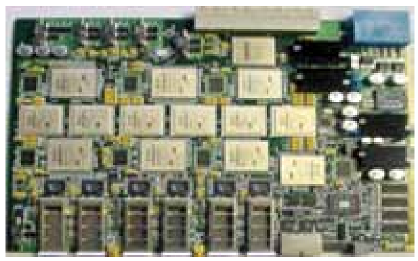


Figure 2. The ACRA System Concept



Frequency Synthesizer

Frequency Down Converter



Digital Beamforming Circuit Board

Printed Circuit Board Antenna Array

Figure 3. ACRA System Components

The performance requirements for the ACRA system must span the requirements of multiple legacy systems. Indeed, the overarching goal and primary challenge facing the program is to design and build an affordable, scalable system capable of replacing multiple legacy systems. Chief among the requirements is the capability to accurately search a large volume at long range; to update this search at a sufficiently high rate to track objects of interest; to mitigate the effects of sea clutter and anomalous atmospheric conditions on radar performance; and to possess the capability to mitigate hostile jamming. Trade studies are underway to optimize the system architecture to demonstrate scalable system performance and system cost to meet the needs of various potential end users. For example, to effectively search a large volume (at long range) with a sufficient update rate requires a high-power TX antenna emitting a wide beam, coupled with a large RX antenna forming multiple, simultaneous RX beams. NSWCDD RX antenna trade studies are examining array architectures and their resulting patterns. Figure 4 shows the generation of a low sidelobe pattern based on a triangular element grid, further based on a staggered arrangement of circuit board panels.

NSWCDD is also leading the way in defining the system architecture and subsystems requirements forming the backbone of the entire ACRA system. The subsystem technologies include digital receivers, waveform generators, reference clocks, and beamformers. The physical digital and analog interfaces between these subsystems are defined within an open-architecture design concept based on open, standard, nonproprietary protocols and signal formats, as initially developed and defined by ONR's DAR program. The benefits of an open-architecture design are many, including subsystem development in a competitive environment to reduce system cost; the use of relatively inexpensive, readily available commercial products and standards; ease of hardware upgrade (technology refresh) during the life of the system; and ease of adding future functionality (technology insertion) once the system is deployed.

The Navy's current fleet of shipboard long-range surveillance radars is approaching obsolescence. Moreover, future naval radar systems are expected to be largely digital in design. The ACRA program represents an opportunity for developing a new, modern, affordable, and scalable Navy radar asset based on a digital open-architecture concept. Over the next 5 years, NSWCDD scientists and engineers will be working to make this concept a reality. As a result, Navy and Marine Corps warfighters will experience improved performance in a reliable system for shipboard surveillance and combat support.

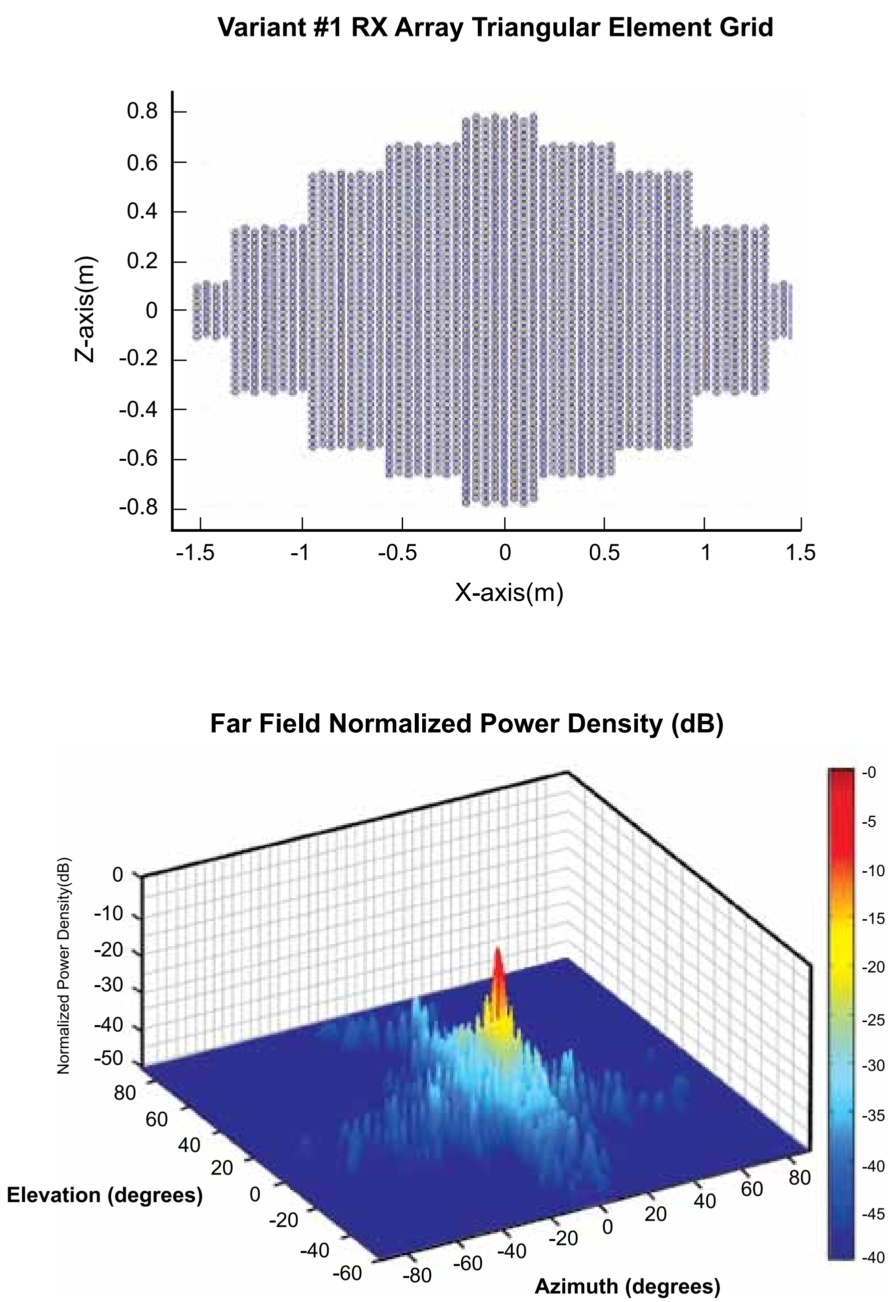
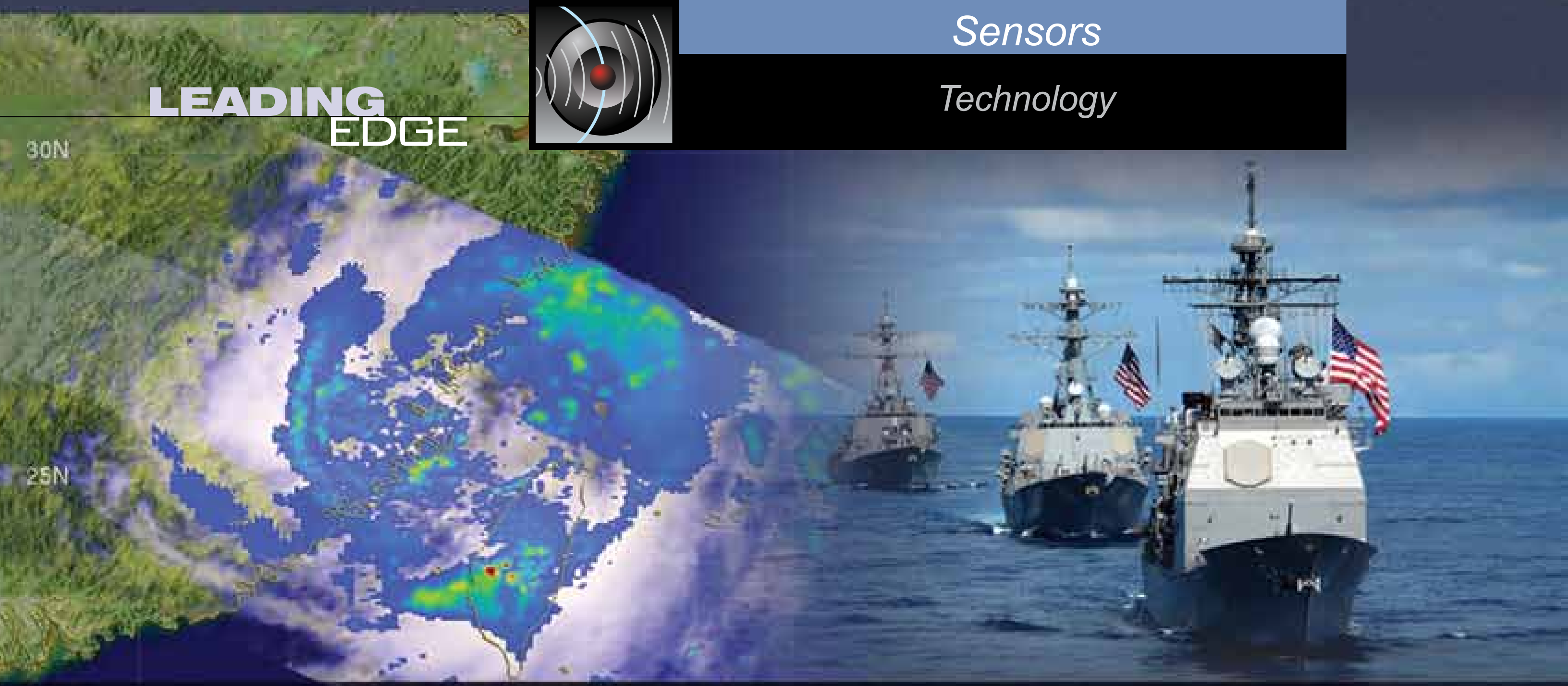


Figure 4. Low Sidelobe Pattern Based on a Triangular Element Grid, Further Based on a Staggered Arrangement of Circuit Board Panels



Littoral Radio Frequency System Performance Forecasts

By Robert E. Marshall

Radio frequency (RF) propagation refers to the impact of the atmosphere on RF energy as it flows through the atmosphere between antennas. RF propagation is influenced by the clear atmosphere, rain, fog, cloud, snow, ice, and electron densities found in the ionosphere. Propagation in the clear atmosphere can significantly impact RF system performance. Refraction is the bending of light energy or RF energy. Refraction at optical wavelengths is observed when one inserts a pencil in a glass of water and the pencil appears bent at the top of the water column. The bending of light energy by small raindrops produces rainbows. You cannot see RF energy as it is bent in the clear atmosphere, but on a perfectly clear day with no visible clues from the atmosphere, radar may suffer severe refraction and subsequent poor mission performance. As RF energy leaves the antenna, it is bent by the atmosphere in ways that can easily refract it away from the intended target. RF energy is especially attracted to areas in the atmosphere with high humidity or low temperatures. Radar operators who do not account for refraction can be easily fooled by what the radar signal is telling them about targets.

Navy surface radars and communication systems operate in a shallow layer of the atmosphere called the marine atmospheric boundary layer (MABL). The MABL can extend from the sea surface up to as high as 1000 m—a complex environment where humidity, temperature, and refraction vary wildly. The MABL is drastically more complex within 100 km of the coast than it is over an open ocean. RF energy can be bent or refracted in various ways in the MABL. Figure 1 illustrates the four RF refraction categories.

Standard propagation or refraction has roots in the U.S. National Advisory Committee on Aeronautics (NACA) 1922 definition of a standard atmosphere. The NACA standard atmosphere was necessary to provide a standard for aircraft performance. Unfortunately, the standard atmosphere is more likely to be found above the MABL and typically provides a false impression of radar performance within the MABL. Super-refraction occurs when the RF energy is bent just enough such that it hugs the curvature of the earth. RF energy travels great distances in the MABL when it is super-refracted, allowing radars to see targets and communications systems to operate at abnormally long ranges. This propagation benefit is often complicated by the potential accompanying liability of folded land clutter and radio frequency interference (RFI). Subrefraction occurs when higher humidity is found at the top of the MABL, and RF

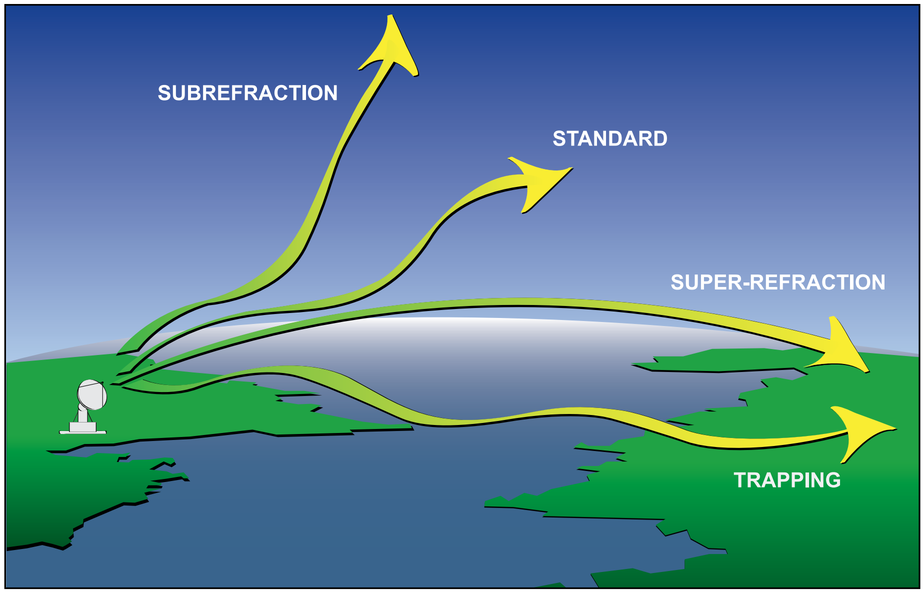


Figure 1. RF Propagation or Refraction Categories

energy rapidly bends away from the earth's curvature. Subrefraction is a relatively rare event, but when subrefraction occurs, radar detection of targets in the MABL becomes significantly more difficult, and the naval surface platform becomes more vulnerable to an approaching target. Trapping or ducting occurs when higher temperatures are at the top of the MABL, and higher humidity is at the bottom of the MABL. The RF energy is trapped or ducted between the top and bottom of the MABL and bounces back and forth as it propagates away from and back to the antenna. Ducting develops radar holes or skip zones where targets cannot be detected, and it also produces areas of sea clutter, where targets are difficult to detect.

To make matters worse, the MABL is forever evolving, driven primarily by the land/sea temperature difference. During daylight hours, the sun heats the land much faster than the ocean often leading to a sea breeze, as the model in Figure 2 demonstrates. Warm, dry air flows offshore at the top of the MABL, and cool, moist air flows onshore at the bottom of the MABL. After the sun sets, the circulation tends to reverse as a land breeze with warm, dry air flowing offshore near the sea surface and cool moist air flowing inshore aloft. As this typically 24-hr cycle progresses, the refractivity field in the MABL is constantly readjusting and constantly impacting RF system performance.

Accounting for these constantly varying refractive and propagation influences on RF system performance is essential for operations, acquisition engineering, and prototype RF system testing. The use of weather balloons, helicopters, rocket weather sounding systems, unmanned aerial vehicles (UAVs), and weather buoys have all been employed to document the refractive environment in the littorals. These are logistically difficult, expensive, and lack the ability to forecast what will happen in the future.

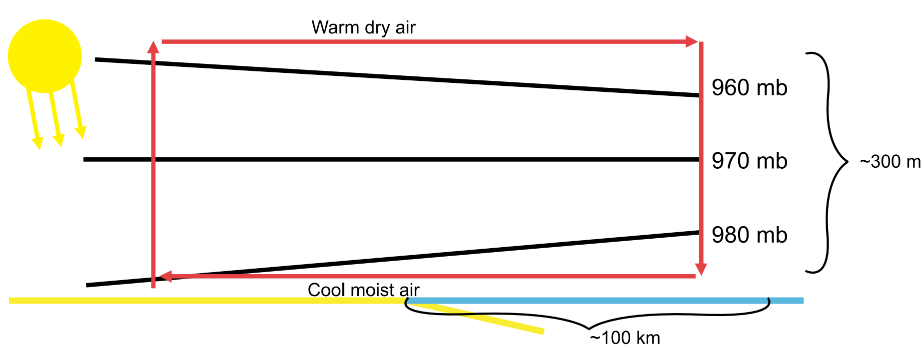


Figure 2. Sea Breeze Circulation

The Naval Surface Warfare Center, Dahlgren Division (NSWCDD) has a 15-year history of research and development in clear-air refraction of RF energy and how it impacts radar and communication system performance. For the last 5 years, NSWCDD has exploited the rapidly maturing technology of numerical weather prediction (NWP) to capture the four-dimensional (4-D) refractive structure of the MABL. NWP is displayed daily by television broadcast meteorologists as time-lapse forecasts of rainfall, clouds, or wind. This same NWP technology can be employed to forecast refractivity in the MABL. NWP models are globally locatable, provide a 48- to 72-hr forecast, and take into account all the land/sea characteristics that drive the evolving MABL refractive structure. There are dozens of NWP models used by military and civilian agencies around the world. NSWCDD runs the Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS). COAMPS is the U.S. Navy medium-scale NWP model developed and supported by the Marine Meteorology Division of the Naval Research Laboratory in Monterey, California (NRL-MRY). COAMPS products are run operationally by the Fleet Numerical Meteorology and Oceanography Center (FNMOC), also in Monterey, California, for many locations around the globe in support of fleet operations.

NSWCDD's COAMPS system consists of two Linux clusters. The research and development cluster named Bean resides at NRL-MRY and supports COAMPS improvements by way of a scientific collaboration between NSWCDD and NRL. As these improvements are validated, they are ported to the operational cluster at NSWCDD named Dutton/Mesos. Dutton/Mesos supports RF test beds at Wallops Island, Virginia, and the Potomac River Test Range (PRTR) at Dahlgren. Example COAMPS model output for both locations is shown in Figure 3. Figure 3 displays temperatures at 2 m above the surface and wind flags at 10 m above the surface. The 1-km horizontal resolution is indicated by the locations of the wind flags. Dutton/Mesos is also capable of simultaneously supporting models at four other global locations.

These same COAMPS models are capable of forecasting refractivity in the MABL. Thus, refractivity is provided every kilometer, every hour out to 48 hr in the future through the depth of the MABL.

The refractivity fields by themselves are of little use to RF engineers until paired with modern RF system models. RF system performance models have been modified in recent years to accept NWP 0- to 48-hr refractivity forecast fields. The coupled model pair can lead to 0- to 48-hr RF system performance forecasts as illustrated in Figure 4.

The Advanced Refractive Effects Prediction System (AREPS) is developed and supported by the Propagation Research Branch of the Space and Naval Warfare Systems Command (SPAWAR)/San Diego. AREPS ingests COAMPS refractivity fields and specific RF system specifications, and computes system performance. Figure 5 is an example of a combined COAMPS/AREPS radar performance forecast for a notional S-band radar located along the edge of the Gulf Stream off the Eastern Shore of Virginia. The white radials along each bearing indicate the range at which a

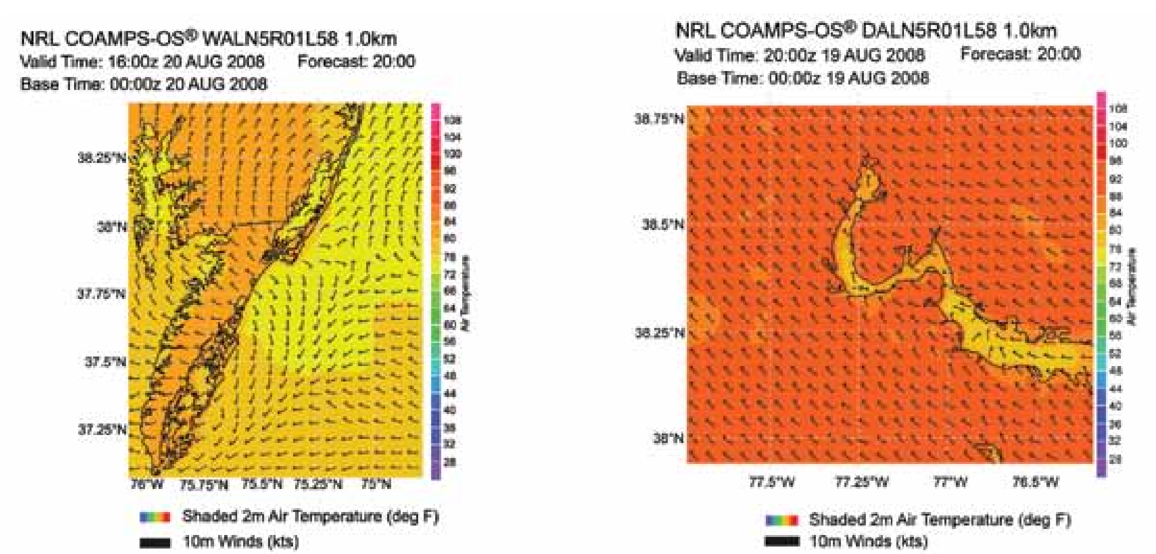


Figure 3. COAMPS Models Over Wallops Island (a) and the PRTR (b) (Wind flags at 10-m ASL and air temperatures at 2-m ASL are displayed.)

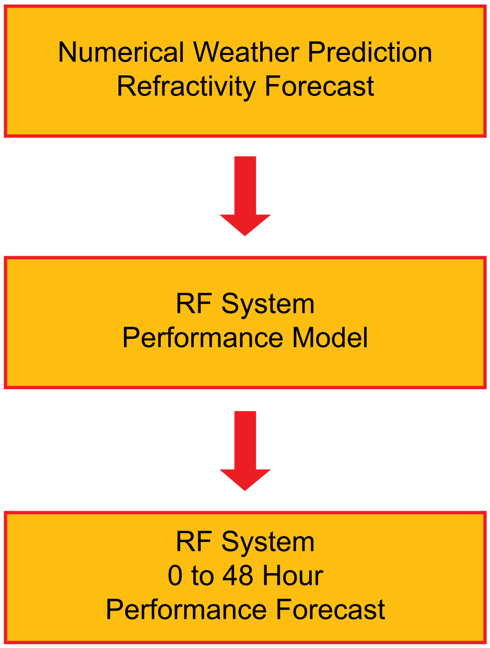


Figure 4. A Radar Performance Forecast Structure

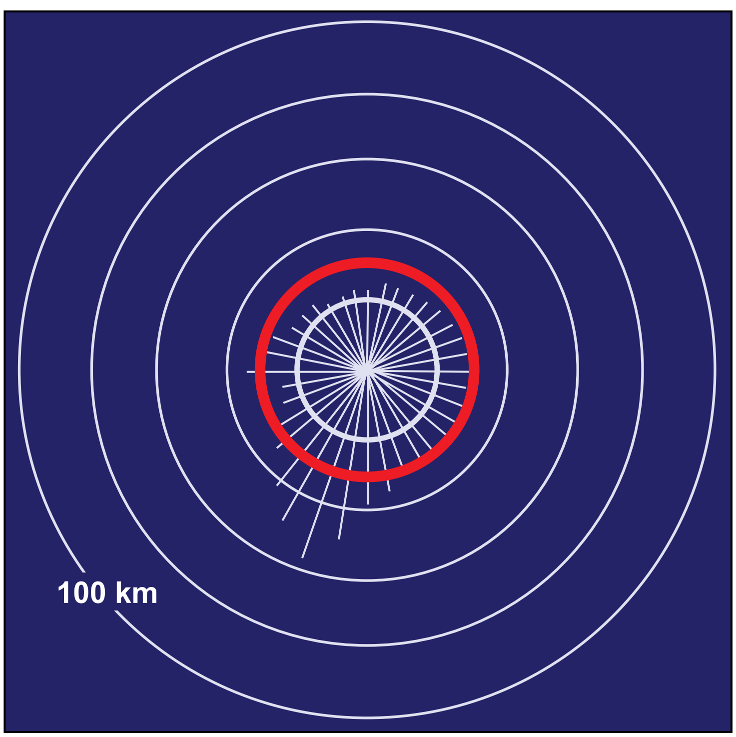


Figure 5. COAMPS/AREPS Model of the Detection Range of a Notional Target 10 m Above the Surface by a Notional S-Band Radar: Range rings are drawn every 20 km. The red ring indicates the detection range in a standard atmosphere.

notional target 10 m above the surface is detected by the notional S-band radar. The variation in detection range with bearing is indicative of how the refractivity field can vary in the MABL. The red ring indicates the detection range in a standard atmosphere. The reduced detection ranges relative to a standard atmosphere indicate areas of subrefraction to the north of the ship. The extended detection ranges southwest of the ship are due to an area of super-refraction. These azimuth-dependent predictions of radar detection range are due primarily to the spatial changes in MABL structure as it reacts to the significant changes in sea surface temperature found along the edge of the Gulf Stream. All these atmosphere and sea surface impacts are captured by COAMPS.

Refraction—or the bending of RF energy—if not accounted for, can severely impact the performance of naval radar and communication systems operating in the MABL. These impacts influence operations, acquisition engineering, and prototype RF system testing. By combining modern numerical weather prediction models with RF system models, it is possible to create site- and time-specific littoral RF system performance forecasts. The current technology is qualitative but has been used NSWCDD to support RF acquisition engineers, prototype RF system test engineers, and operational decision-makers. A strong research effort at NSWCDD aims to make significant increases in littoral RF system performance forecast accuracy in the next 5 years. This same NWP technology is being employed by NSWCDD to provide chemical agent transport and dispersion forecasts, and sound propagation forecasts. Each of these forecasting capabilities will help to ensure that warfighters are armed with effective capabilities and accurate information necessary to fight and win in the electromagnetic environment.

Infrared Sensor and Image Processing for the Chemical Agent Plume Tracking Capability

By Dean Zabel

Chemical agents, when dispersed into the air, form plumes or clouds of particles that can impact warfighters and others in the immediate vicinity. Moreover, just as clouds in the sky form, move and dissipate, so do chemical agent plumes. Unlike clouds in the sky, however, chemical agent plumes might not be easily visible or detectable. Thus, warfighters could be exposed to chemical agents without knowing it, thereby endangering their lives and missions. Consequently, a means to test the capabilities of developmental chemical agent detection systems was needed to ensure that those systems provide the promised protection when deployed. The Chemical Agent Plume Tracking Capability (CAPTC), developed at the Naval Surface Warfare Center (NSWC) Dahlgren, provided a way to track chemical agent plumes to provide that testing capability.

CAPTC was designed to provide a referee capability for testing chemical-agent detection systems. A refereed capability refers to an unbiased measurement of the presence of a chemical-agent plume against which to compare the performance of the system under test. As such, the CAPTC operator will know at the start of a test which chemical is present in the plume. This permits the operator to configure CAPTC optimally for a particular simulant chemical agent release. The visual display provided by CAPTC also serves as a tool to assist the test director in conducting system tests. CAPTC employs near real-time tracking of chemical agent plumes using infrared (IR) images of the plume's location and extent, as determined from two or three locations.

Previous IR Camera Testing

Earlier testing using IR cameras was performed with the Joint Service Lightweight Standoff Chemical Agent Detector (JSLSCAD). Those tests demonstrated the need for very sensitive long-wave infrared (LWIR) cameras to provide near real-time plume tracking.[1] During those tests, it was found that the vapor plumes of a chemical agent simulant provided a low contrast to the ambient scene. This then required a significant amount of posttest processing time to make the plumes detectable. In order to provide near real-time imagery, very high-speed processing of the IR video was found to be required. This article overviews CAPTC, its IR camera requirements, and the software integration and architecture needed to make the system work.

The IR Camera Problem

The testing of chemical agent plumes must be carried out using simulants since actual chemical agents cannot be used. Because of their nature, the simulant plumes of interest to CAPTC are difficult to detect with an IR camera. The simulant is entrained as an aerosol in a high-velocity, high-volume flow of ambient air. Thus, the aerosol plume has very little temperature difference from the surrounding air into which it is injected. The mission of the chemical agent detector is to detect low concentrations of chemical agents. Thus, the content of the plume is not greatly different from the surrounding air mass against which it is to be detected. The requirement to be able to track the simulant plumes in near real time makes the problem even harder.

The IR cameras used for the JSLSCAD tests were wideband microbolometers. Microbolometers generally have detection bands from about 7.5 μ to 13.5 μ. This band more than covers the spectral characteristics of the simulants used in the JSLSCAD testing. However, microbolometers are not particularly sensitive. The microbolometers used for the JSLSCAD tests had minimum resolvable temperature differences (MRTD) of about 0.1°K. When viewed live, subtle changes in the IR scene caused by the vapor plume could sometimes be detected by the camera operator, but not always.

The posttest image processing for JSLSCAD tests used frame averaging. Up to 15 video frames were averaged to enhance the plume sufficiently to ascertain its position and size. This process was very labor intensive and time-consuming. The IR video collected for JSLSCAD tests was at a low frame rate of 5 frames per second. This meant that frame-to-frame registration was difficult to accomplish because both the camera and the plume generator were moving. This low frame rate was selected to manage the storage requirements for the digital video data. In retrospect, it would have been better to record the camera's maximum 60 frames per second digital video. An even higher frame would ease the frame-to-frame registration process. This became one of the factors driving selection of IR cameras for use in CAPTC.

Camera sensitivity becomes a limiting factor in how fast a frame rate may be utilized to collect enough photons to have a viewable image. As stated above, microbolometer technology is not very sensitive. To gain sensitivity, one needs to go to IR cameras that have cryogenically cooled detector arrays. Cooling the array and its associated readout electronics greatly reduces the sensor's noise by decreasing random electron motion. Commercial cooled cameras have achieved MRTDs in the 0.025°K range. However, most cooled LWIR cameras do not have the full detection-band capability needed to detect the simulants of interest. One of the simulants, sulfur hexafluoride, has a single spectral feature at about 10.6 μ. Thus, a camera detection band out to at least 11 μ is required.

Cooled LWIR cameras tend to have detector arrays of two types: quantum well infrared photodetector (QWIP) and detector arrays made from mercury cadmium telluride (MCT). Both types can be very sensitive. QWIP cameras have spectral detection bands of about 7.7 μ to 9.2 μ. Most MCT cameras have a similar detection band, though MCT can be formulated for wider detection bands. Unfortunately, few typical applications require the wider detection band, making the wider band MCT arrays much more expensive.

Spectral filtering also helps when the object to be detected exhibits emissive or absorptive spectral characteristics that are much narrower than the spectral response of the detector. Filtering helps by limiting the background to the spectral region of the object to be detected. The three simulants typically used in testing have different spectral characteristics such that a different filter would be optimum for each. This made it desirable to get a camera with an integrated filter wheel capable of holding at least four filters. The integrated filter wheel makes it possible to quickly select the optimum filter, or no filter at all, since CAPTC needs only three for each particular test run. The use of spectral filtering also drove the need for high camera sensitivity due to an increase in loss from the additional optical element.

The Camera Solution

An extensive search was performed to identify a commercially available IR camera to meet the needs of CAPTC. One MCT camera was located that had a detection band from 7.7 μ to 11.6 μ and included an integrated four-hole filter wheel. This was the CDIP Jade VLWIR. The Army's West Desert Test Center at the Dugway Proving Ground, Utah, had also selected this camera for a similar application. Between the time of selection and time of purchase, the Jade VLWIR was updated to the Titanium SC7900.

The Titanium is a very sensitive camera, with an MRTD < 0.025°K using a 320 horizontal × 256 (240 displayed) vertical MCT array. It supports a frame rate of 90 frames per second for full frames, with on-the-fly selection of any of its four filter wheel holes. The control and video output interface is gigabit Ethernet. The Ethernet interface is an improvement over the older RS-422 for digital video plus RS-232 for control used by the Jade. A software development kit was purchased with the camera to allow development of a control interface optimized for CAPTC.

The spectral characteristics of each of the three simulants were used to determine an optimum filter to use for each simulant. The specifications of the filters were: 7.75 μ to 9.25 μ, 8.6 μ to 10.6 μ, and 9.9 μ to 11.3 μ ±1% for each value.

The final piece of the IR camera is the optics. The JSLSCAD testing involved sensor-to-plume ranges of from 500 m to 6 km. The variation in ranges was needed to assess the sensitivity of the chemical agent detection system under test. Sometimes a plume release close (1.5 km) to the test system would be followed by one a long distance (5.5 km) away from the test system. Keeping the plume in the field of view and yet having sufficient resolution for the needed detail over this span of ranges dictated the use of multifocal optics. Quick physical access to the camera system would not be possible because the camera system needed to be environmentally protected from weather and RF emissions. Focusing and changing from near optics to far optics had to be accomplished quickly, so the optics needed to be remotely controllable. An appropriate commercial off-the-shelf multifocal lens had already been interfaced with the Titanium camera. The lens from StingRay Optics had triple field-of-view optics. It was fully controllable using a control box and 50-ft cable that came with the lens. The focal lengths were 75/150/300 mm, providing fields of view with the Titanium of 7.3° x 5.5°/3.7° x 2.8°/1.8° x 1.4°, respectively. The Titanium camera integrated with the triple field-of-view lens is shown in Figure 1 with the mounting plate portion of its environmental enclosure.

Figure 2 depicts a sample of images acquired by the Titanium camera. Shown are emissions from one of the Morgantown power plant stacks in Maryland at a distance of approximately 2.5 nmi. The first image is a basic IR image. The second image utilized some of the image-processing capabilities of the Altair software purchased with the Titanium camera. The Altair software package provided the ability for a frame-to-frame differencing view, which was done by subtracting one camera frame from the next. The resulting image showed only what changed between the two frames. The Altair software provided great posttest analysis capabilities when supplemented by software developed at NSWC.

Test Environment and Basic Data Capture Architecture

The software developed at NSWC provided the integration of a number of test assets, ships, or platforms with data-collection equipment, and the equipment aboard each asset to facilitate the test data collection of a given test event. CAPTC, as a system, encompasses the data-collection equipment on all of the assets tied together by the software. A notional test situation that would

Figure 1. Titanium Camera with the Stingray Optics on the Mounting Plate Part of Its Environmental Enclosure

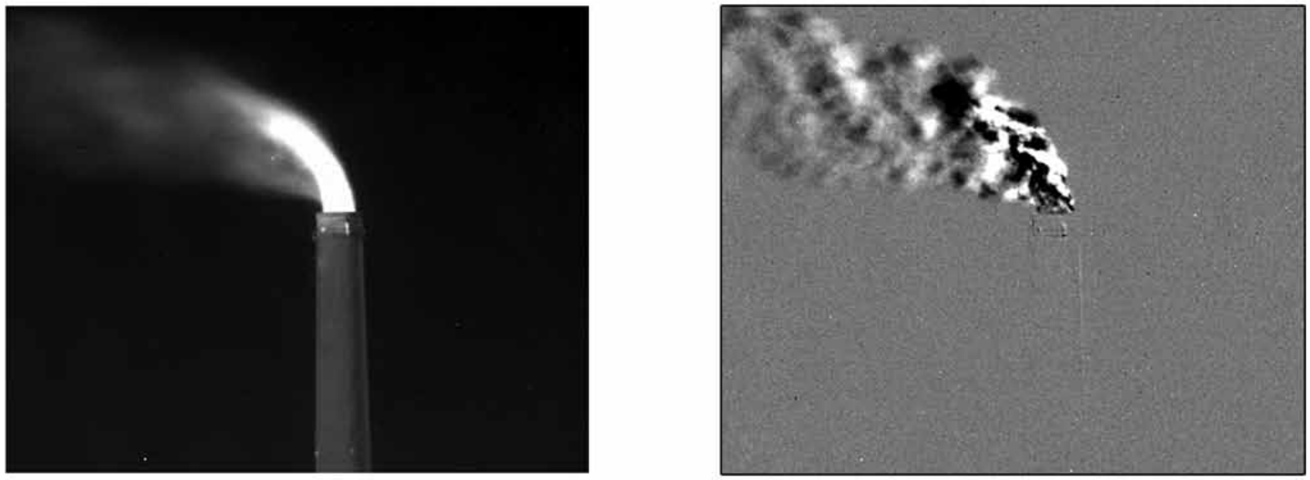


Figure 2. Sample Infrared Images Acquired by Titanium Camera

utilize the CAPTC environment is depicted in Figure 3. Each test asset is installed with test data-capture equipment that stores all local data and data broadcast from other assets. As a simulant is dispersed by the *Gatlin*, a Naval Surface Warfare Center, Dahlgren Division (NSWCDD)-owned ship outfitted with a blower system is used to generate the simulant plume, the data-capture equipment tracks and records the location of each asset and the calculated position of the chemical simulant plume. The basic equipment and data capture environment is shown in Figure 4. Figure 5 is a photograph of the *Gatlin* pierside preparing for JSLSCAD testing.

Each test asset or ship utilizes a local Global Positioning System (GPS) to track its current location and transmits this information over the low-data-rate (LDR) communications link. The LDR link is an omnidirectional link and provides for system commands and asset tracking information to be transferred to the main processing unit or the command console. The asset tracking information is crucial to the environment, as it is necessary to reposition or reorient the directional high-data-rate (HDR) link antennas. The HDR link is utilized to transfer the IR and situational awareness (SA) video to the command console.

A depiction of the command console Graphical User Interface (GUI) incorporating IR imagery, modeling and simulation (M&S) output, SA video, and position heading data from each of the platforms in the test is shown in Figure 6. The operator has multiple data windows that can track the multiple test assets of the CAPTC environment. The user interface is separated into upper and lower viewing areas. The lower display area provides a quick look at the status of each asset (i.e., latitude, longitude, and course) and the status of each CAPTC processing component executing on that platform. The upper display area provides the user with the ability to toggle through various options

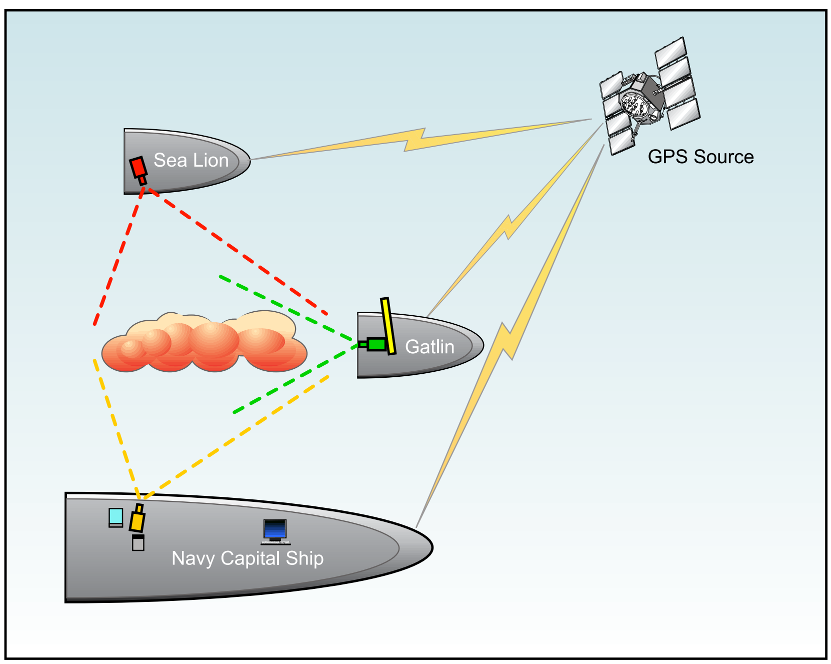


Figure 3. Notional CAPTC Test Environment

to view the IR video, the situation awareness video, the predicted weather information, and the status of the simulant plume dispersal.

In addition to the GUI, test event data is sent to a simulation display window that tracks and displays each test asset and the simulant plume in a 3-D display environment using the Simulation Display (SIMDIS) application developed by the Naval Research Laboratory (NRL). As each test asset sends its positional data (latitude and longitude) to the command console, the console sends the information to the SIMDIS for rendering.

Conclusion

The CAPTC mission presented some complex technical challenges. In solving those challenges, an IR camera with appropriate capabilities, filters, and optics was found that—when coupled with the software and architecture developed by engineers at NSWC Dahlgren—enabled the detection and tracking of difficult-to-see simulated chemical agent plumes. Moreover, a data acquisition system was designed and assembled by NSWC engineers that handled the significant image processing requirements. A user interface was developed that was capable of meeting the rigors of the refereed testing environment. A user interface was developed that was capable of meeting the rigors of the refereed testing environment. The system was successfully demonstrated during the month of July 2009. The CAPTC system provides a unique, new capability to the testing community that will ensure fielded chemical agent detection systems will help protect warfighters by alerting them to chemical agent plumes that might otherwise go undetected.

Acknowledgments

James Tharp (iO Technologies, Inc.) and Gloria Vaquer (NSWCDD) contributed to this article.

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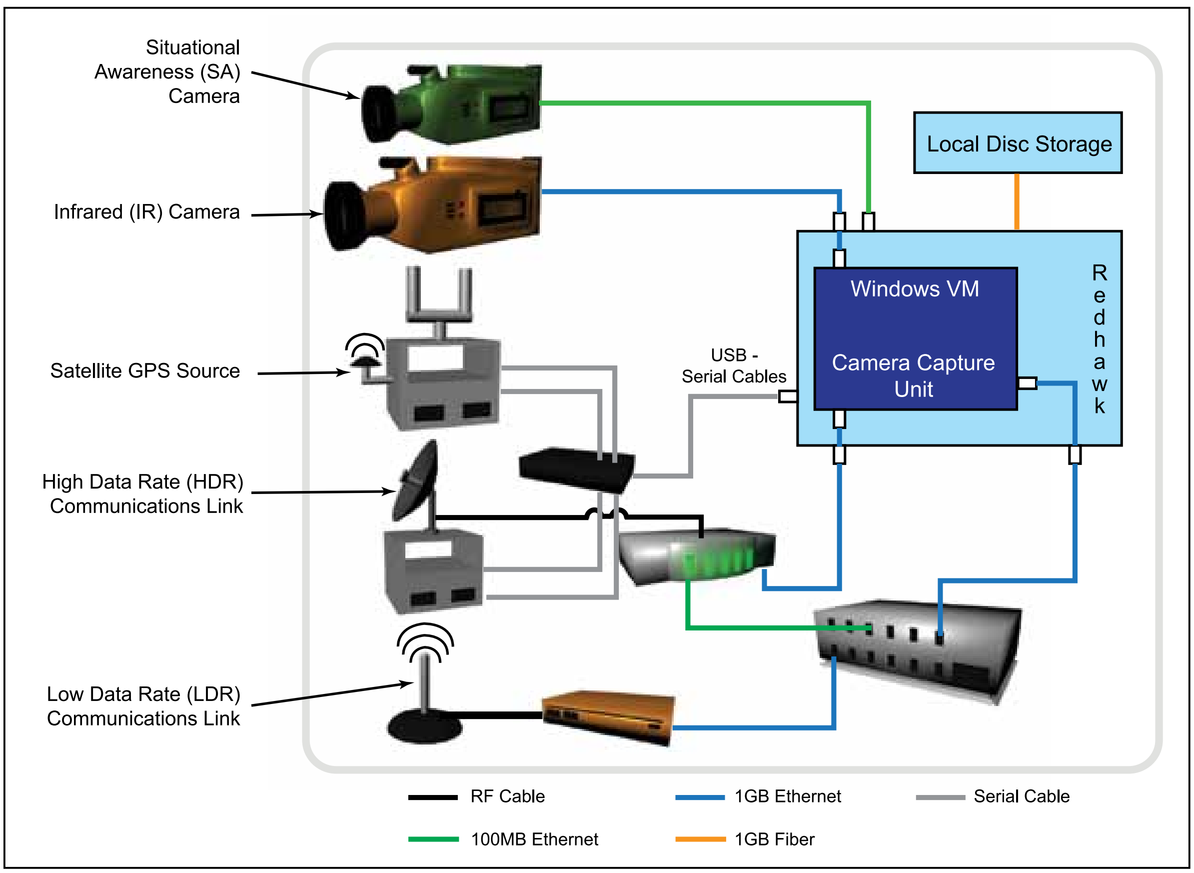


Figure 4. Basic Data-Capture Architecture

Figure 5. *Gatlin* Simulant Plume Dispersal Boat Preparing for JSLSCAD Testing in Summer 2004

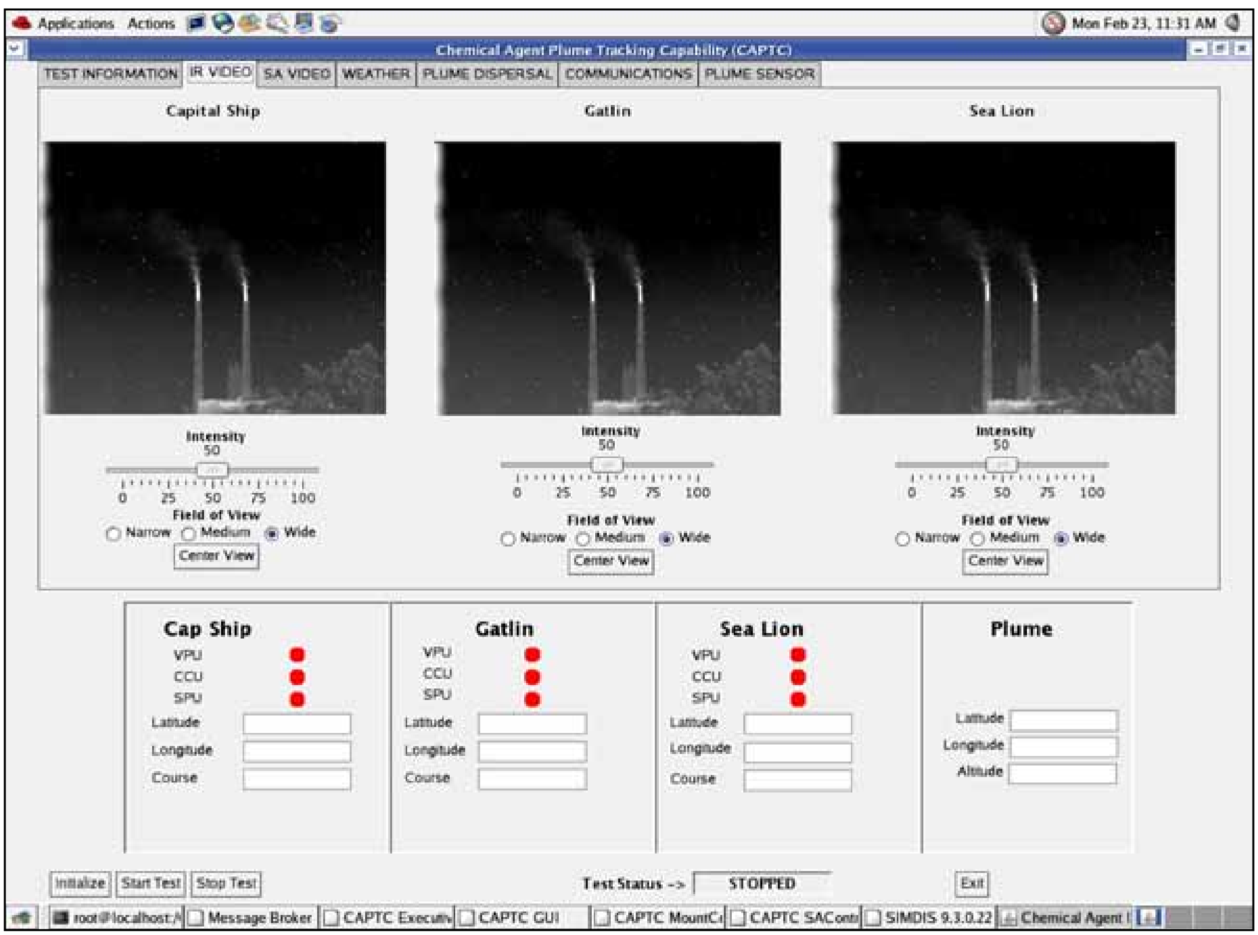
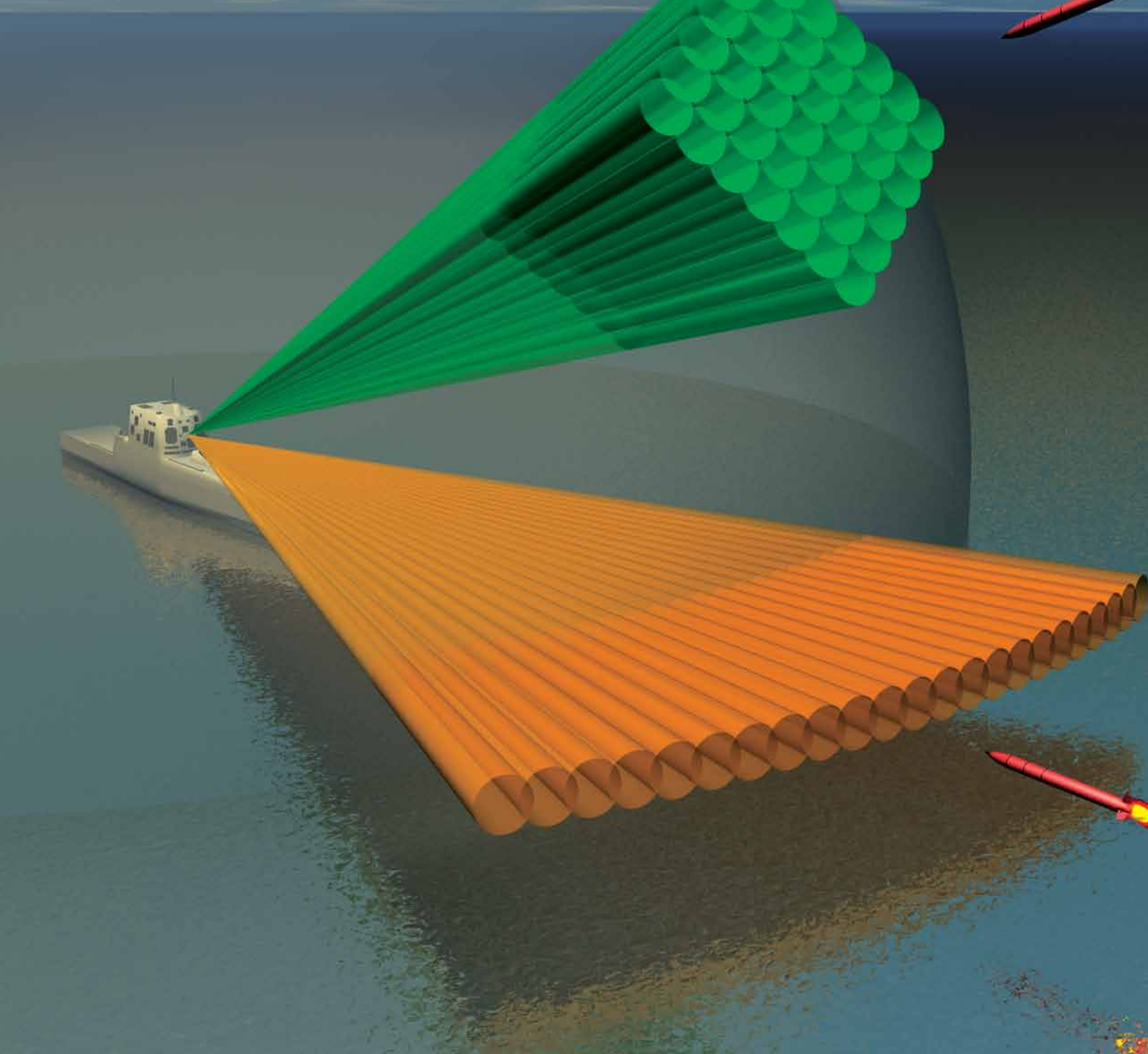
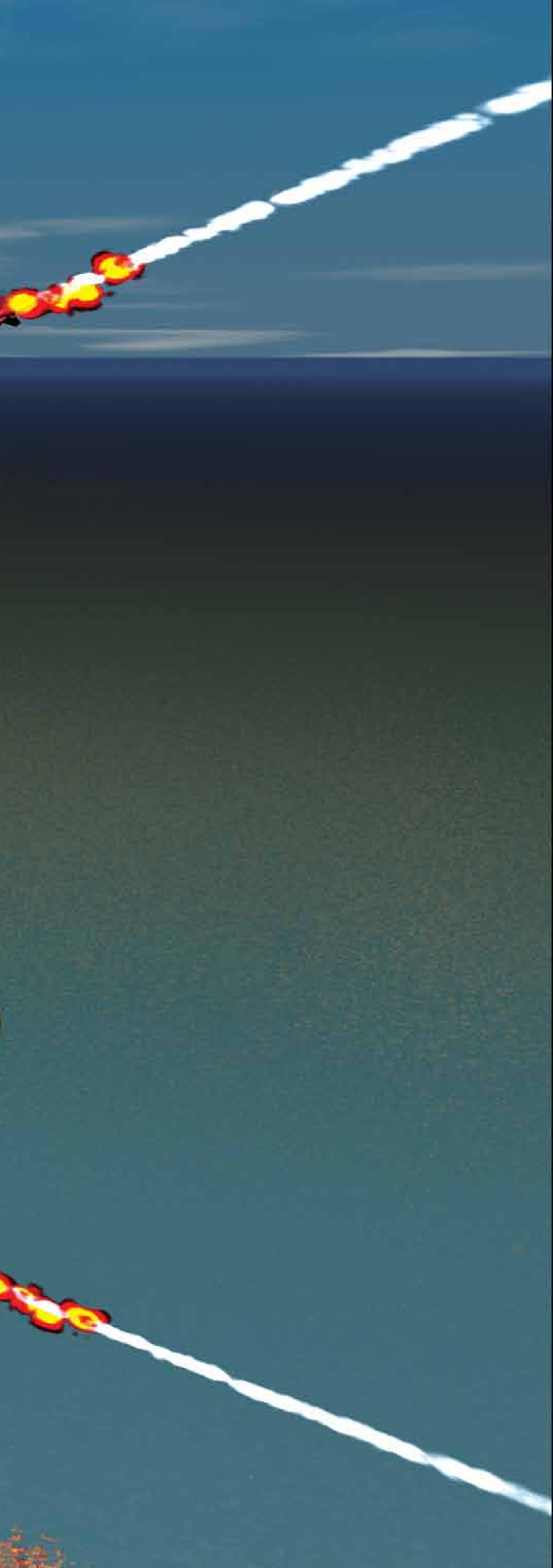


Figure 6. Sample CAPTC Command Console GUI

Digital Array Radar Test Bed

By Ronnie A. Stapleton and Carlos G. Tua





Digital Array Radar Test Bed

The Theater Air and Missile Defense (TAMD) radar systems envisioned for use in next-generation naval surface combatants are anticipated to include high-power apertures operating at S-band. While the high power of these systems is driven by ballistic missile defense requirements, the radars are, by necessity, multifunction and will also be required to detect and track targets at low elevations in clutter. This poses a problem, as the instantaneous dynamic range required of the system to support operation in clutter is not easily met with traditional receiver-exciter architectures built with conventional components. Additionally, the high power and narrow beams required for missile defense functions results in a system that is unable to search the requisite volume of space in a reasonable time frame.

To mitigate these issues, radar system architecture has been developed that uses multiple receiver-exciter subsystems operating in parallel in a distributed fashion. This results in a system with increased dynamic range and stability, as well as the ability to search with clusters of beams to increase the system volume search update rate.

This article provides an overview of the Digital Array Radar (DAR) Project, sponsored by the Office of Naval Research (ONR) (Code 313) that is performing risk reduction for next-generation TAMD S-band radars and on a test-bed system that is being constructed to validate system calibration and calibration maintenance. The DAR concept is depicted in Figure 1.

The DAR effort concentrates on developing an open, modular system architecture that applies to the entire radar system, including the development and demonstration of subsystem technologies in the areas of receiver-exciters, digital beamforming and signal processing. A significant attribute of this

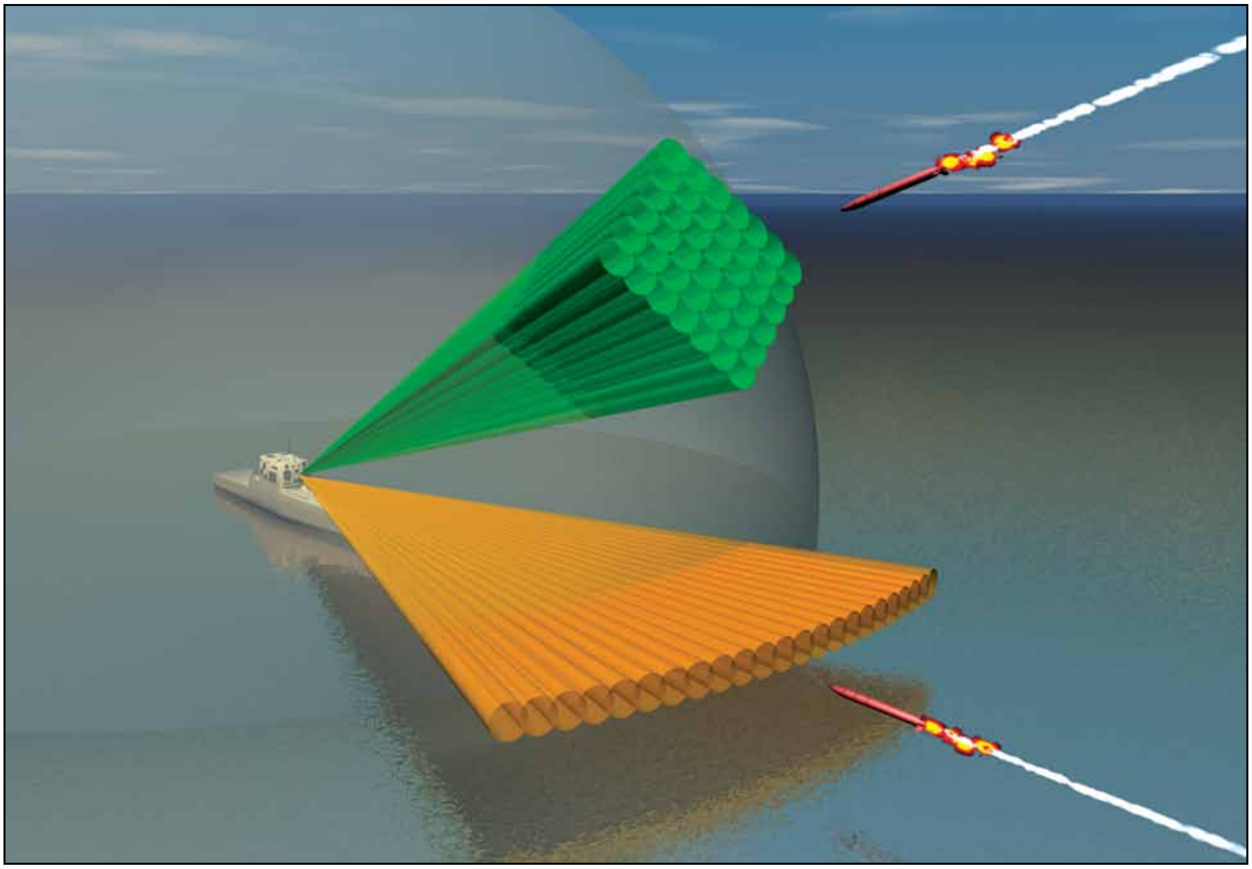


Figure 1. DAR Open-Architecture Concept That Enables Multiple Simultaneous Beams and Multifunction Capabilities

architecture is the use of an interface control document that specifies the messages used among all subsystem elements. A second significant attribute of the design is that all system and subsystem control is affected with commands based on time of day, resulting in only two interfaces—one for control messages and one for time—entering each subsystem. These two elements allow subsystems to be modular in design, which in theory, allow subsystems from multiple vendors to be used to create the overall system. To date, the following participants have collaborated on various elements of the DAR system development:

- ONR
- Naval Surface Warfare Center, Dahlgren Division (NSWCDD)
- U.S. Naval Research Laboratory (NRL)
- General Dynamics Advanced Information Systems
- Lockheed Martin Government Electronic Systems
- ITT Corporation
- REMEC Defense and Space

The DAR program has progressed to the point where end-to-end radar is required to effectively test the radar subsystems. To this end, a test bed is being constructed that will serve as an instrumentation radar with enough functionality to retire risk through engineering tests while demonstrating radar functionality representative of that required in a tactical system. Figure 2 shows the DAR Open-Architecture Block Diagram. Construction of this test-bed radar is being accomplished by integrating all of the elements behind the antenna, which have been the focus of the DAR program, along with a surrogate array antenna and associated electronics. The test bed will implement the five subsystems marked in blue, while the gray Combat and Navigation System blocks are part of a tactical system and, as such, will not be implemented in the prototype.

Although the focus of the DAR program has been on developing the radar subsystems behind the antenna, the additional requirement to build a prototype radar system necessitated an antenna and the associated active-array electronics. In lieu

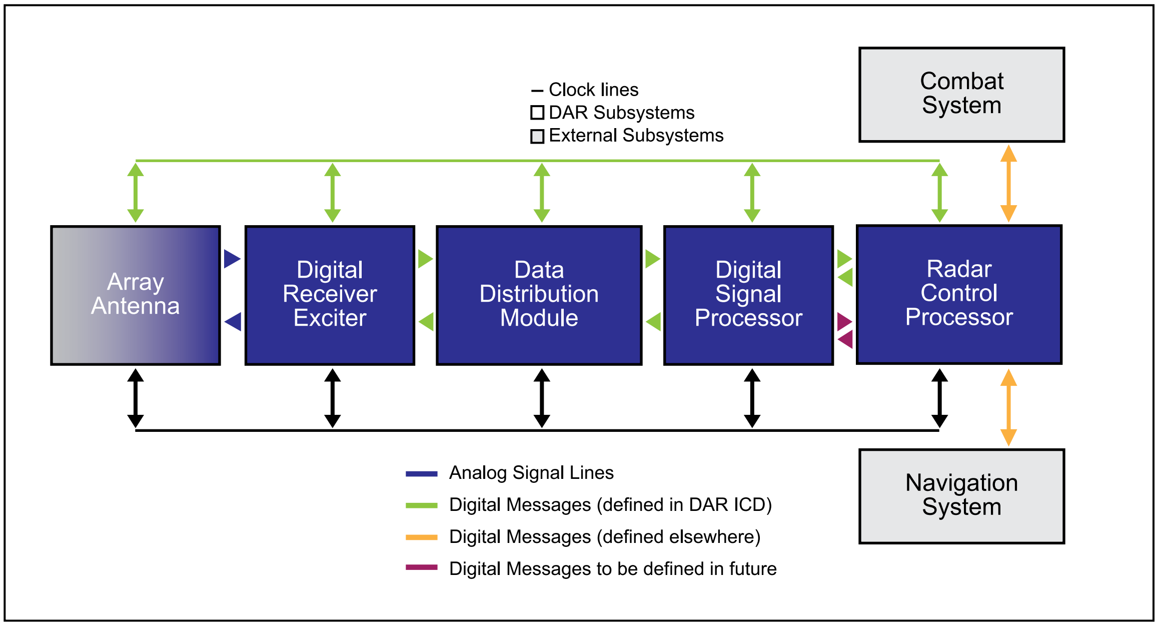


Figure 2. DAR Open-Architecture Block Diagram

of designing a traditional active array with a large number of elements, the DAR program is using a novel pillbox horn antenna array that offers a combination of high gain, low loss, and simple fabrication.[1] This antenna, designed by NRL, has been proven with a four-element prototype and is now being constructed with a 64-element design that will be used in the risk-reduction test-bed radar system. The DAR Test-Bed Antenna Array is depicted in Figure 3.

In order to avoid the development cost associated with a conventional active-array, transmit-receive module, the DAR electronics associated with the antenna are built using individual power amplifiers to provide higher power signals on ***transmit*** and individual low-noise amplifiers to provide low-level signal amplification on ***receive***. They are mounted on a cold plate for thermal management. A prototype can be seen in Figure 4.

The digital receiver exciters used in the system are responsible for conversion of digital data to S-band signals on transmittal and for conversion of S-band received signals to digital data on reception. The data distribution module accepts data from the receiver over an industry standard 10-gigabit Ethernet interface and performs all of the complex mathematical digital beamforming computations in real time required to produce antenna beams. The system signal and control processing functions are implemented in real time with a commercial blade server computer system from IBM. Figure 5 shows each of the subsystem components that will be used to construct the test-bed radar system.

All portions of the test-bed radar system, except for the antenna, were available for testing at the General Dynamics Advanced Information Systems facility in late 2008. In order to facilitate early integration, a microwave-fiber optic delay line and Doppler repeater were used, along with a modest amount of custom-engineered microwave hardware to allow early integration and testing of most of the subsystem elements in a laboratory environment. Figure 6 shows a photo of the microwave-fiber optic delay line and Doppler repeater.

Successful integration, calibration, and testing of the elements in this fashion will greatly accelerate the transition of the radar to a functioning test bed radiating in free space. The test bed is currently

(a)

(b)

Figure 3. DAR Test-Bed Antenna Array: (a) Antenna has been assembled inside a steel frame for rigidity, and (b) Outline of horn and parabolic reflector have been constructed out of aluminum standoffs.

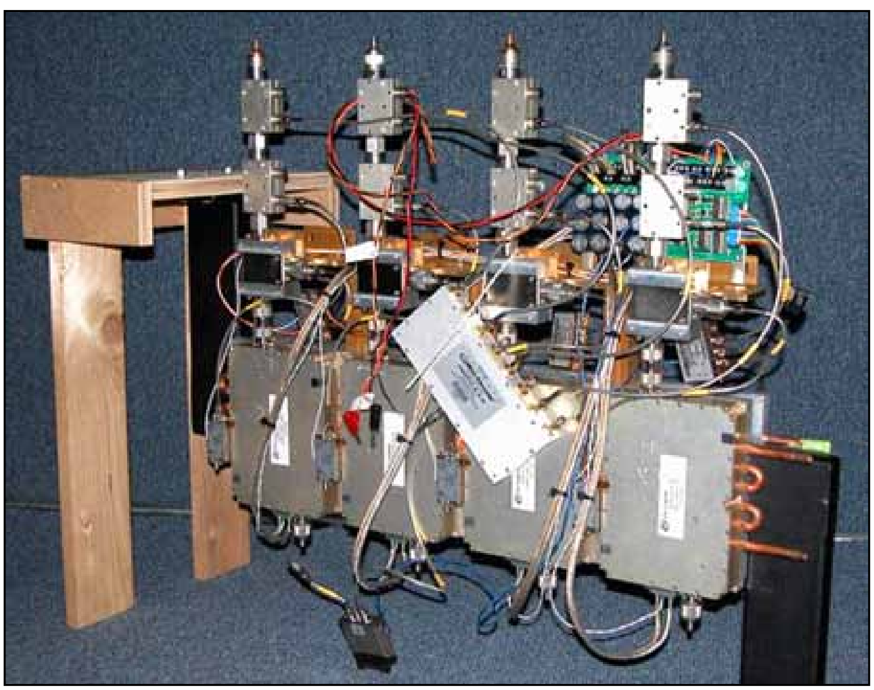


Figure 4. Power Amplifiers, Low-Noise Amplifiers, and Supporting Microwave Hardware and Electronics Mounted on a Cold Plate

DREX

Data Distribution Module

Digital Signal Processor and Radar Control Processor (IBM Blade Servers)

1- and 10-Gigabit Ethernet Network Switch

Figure 5. DAR Test-Bed Subsystems

(a)

(b)

Figure 6. (a) Microwave Hardware and Microwave-Fiber Delay Line; (b) Doppler Repeater

being assembled at NSWCDD's Search and Track Sensor Test Site overlooking the Potomac River. The first phase of the DAR test bed will be based on a four-element design with rather modest capabilities. Throughout 2009 and continuing into 2010, the system will grow to 32 and then 64 channels through the addition of a larger antenna, combined with additional receiver-exciter units and processing subsystems. Activities during this time will focus on calibration and calibration maintenance of the transmit and receive subsystems, which is critical to achieving high-quality antenna patterns and rejection of system clutter.

To date, all development on the DAR program has been accomplished without any contractor-specific intellectual property associated with the architecture and subsystem interfaces. The test bed that is being built will serve as a tool both to highlight the subsystem capabilities to enable transition into a tactical system, but also as a tool for experimentation in areas that can be used to benefit the radar community. Lessons learned from all tests will be shared with both government and industry so that next-generation systems can be successfully designed, built, and ultimately, fielded in the hands of warfighters in order to increase the capabilities of radars to perform their missions in the face of current and emergent threats.

Reference

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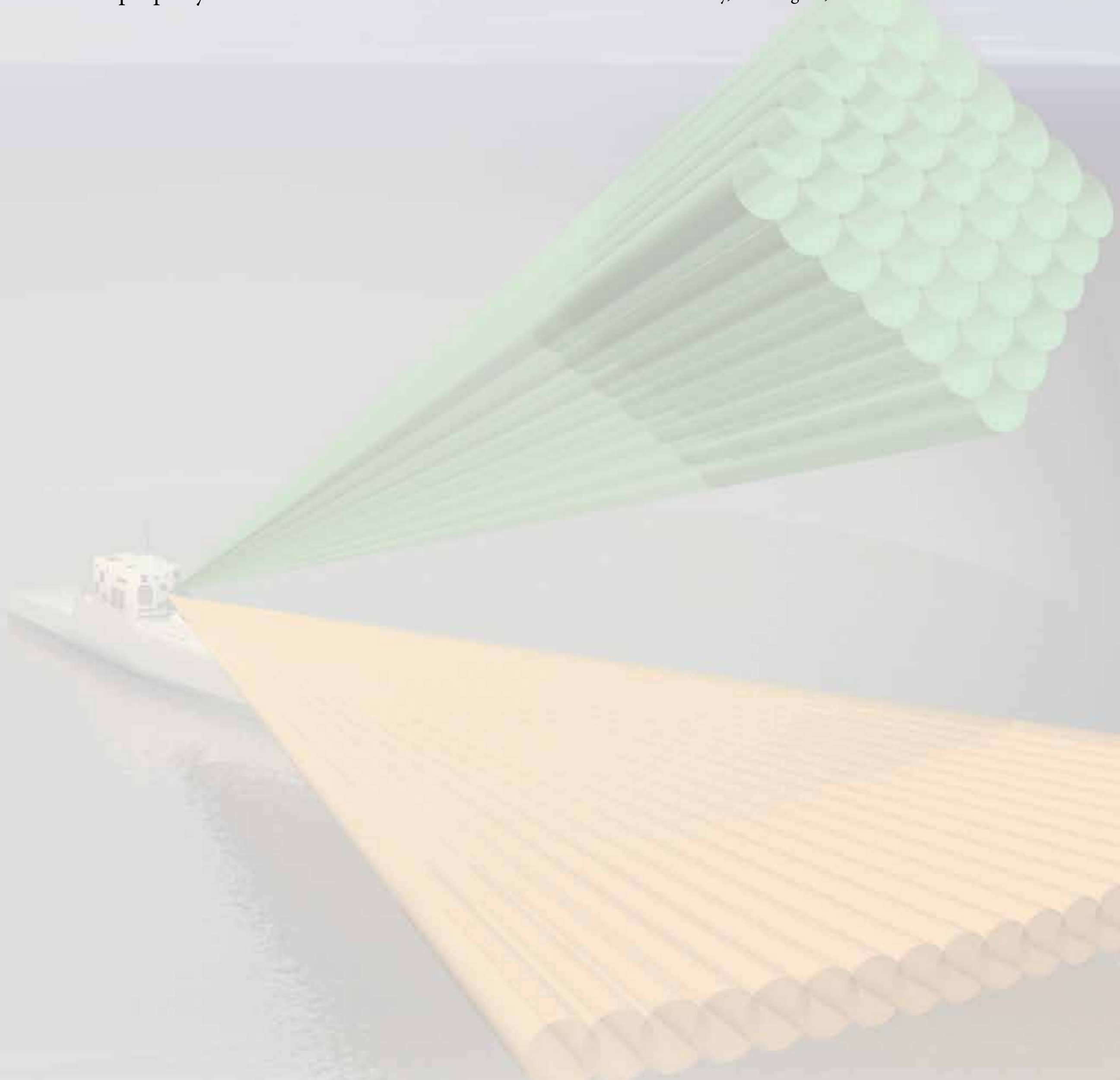


Draft – Working Papers

Multifunction Electronic Warfare (MFEW) Technology Development Program

By Janine Knott

Figure 1. An artist rendering of the *Zumwalt*-class destroyer DDG 1000, a new class of multimission U.S. Navy surface combatant ship designed to operate as part of a joint maritime fleet, assisting Marine strike forces ashore, as well as performing littoral, air, and subsurface warfare. (U.S. Navy photo illustration/Released 080723-N-0000X-001)

The Multifunction Electronic Warfare/Electronic Support (MFEW) Program evolved from the Office of Naval Research (ONR) Advanced Multifunction Radio Frequency (RF) Concept, Future Naval Capabilities. In support of this initiative, a single Advanced Development Model (ADM) contract was awarded to design electronic support functionality per the DDG 1000 Electronic Warfare (EW) specification as a modular, open, scalable system to support capability growth and application across the entire fleet. The Electronic Warfare and EOIR Systems Branch at the Naval Surface Warfare Center, Dahlgren Division (NSWCDD) provided key support as the MFEW System Engineering lead to the Naval Research Laboratory and the prime contractor, Northrop Grumman Baltimore, in the areas of design, requirements assessment, risk assessment, and test and evaluation planning. The 2-year ADM project included the detailed design and ADM build and test, followed by a transition to Naval Sea Systems Command (NAVSEA) in 2008 via the technology transition agreement between ONR and NAVSEA.

Program Goal

The goal of the MFEW Program was to develop a MFEW ADM for the DDG-1000 ship class that demonstrated key electronic surveillance capabilities, including high probability of intercept, precision direction finding, and specific emitter identification. The plan was to conduct MFEW ADM testing that satisfied technology development phase requirements to enable a smooth transition to the system development and demonstrations acquisition phase. The MFEW ADM was leveraged as an opportunity to resolve significant cost, schedule, and performance risks early in the acquisition process. This was accomplished by using modified Surface Electronic Warfare Improvement Program (SEWIP) electronic support equipment to ease backfit integration. The ADM design mitigated critical technical risks, refined requirements, and also permitted experimentation and trade studies that addressed technical system design and development program challenges. Key technical challenges included co-site interference and multipath interference. The program used a modular, scalable, and open architecture capable of supporting additional EW functionality and platform configurations including backfit. The flexibility to handle new threats, the ability to add capability, and the ability to adapt to a ship's radio frequency interference/electromagnetic interference (RFI/EMI) environment were also included in the design. An image of the DDG 1000 is shown in Figure 1 (see title page).

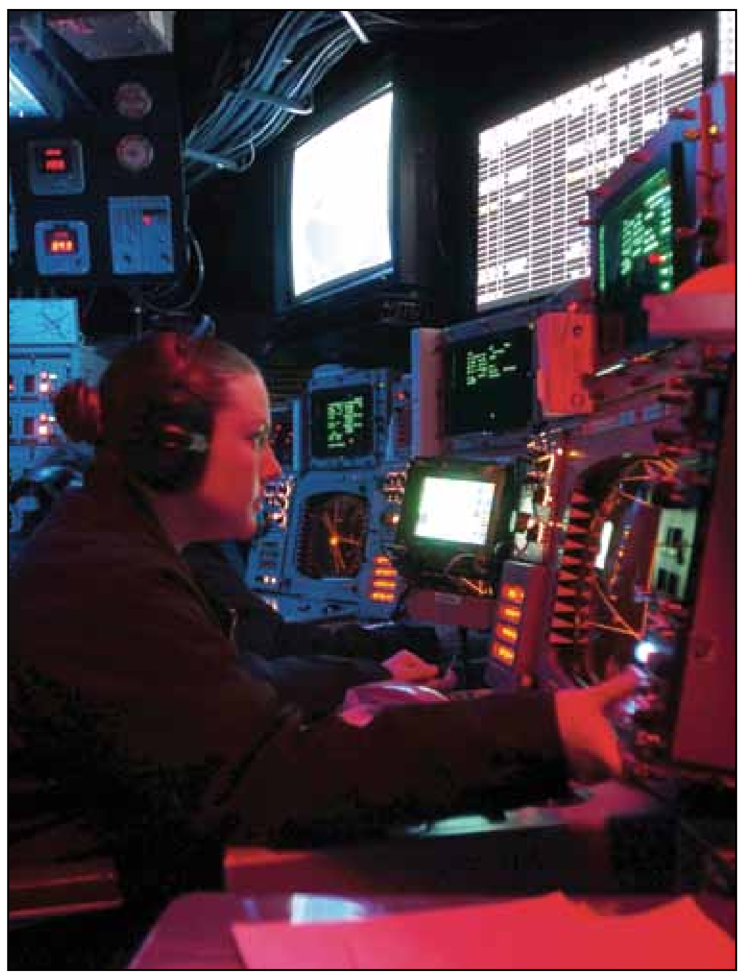
System Architecture and Design

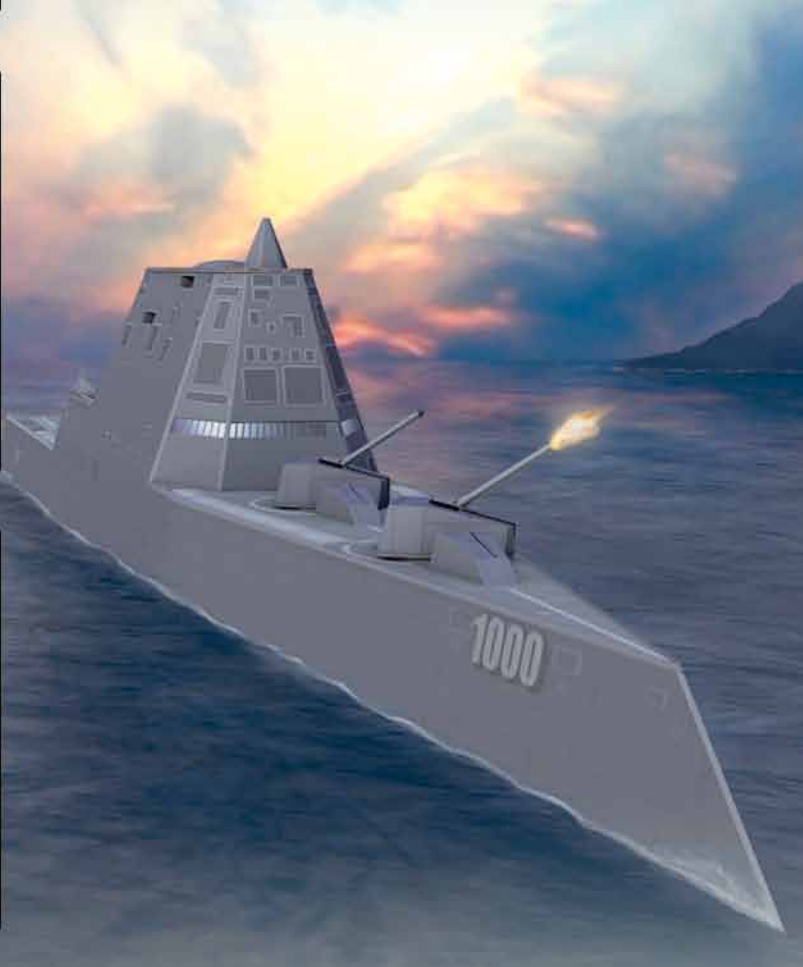
The MFEW ADM consisted of a single-quadrant linear interferometer with a high probability of intercept and precision direction-finding capabilities, as well as a series of digital receivers and advanced pulse processing that provides antiship cruise missile detection and situational awareness in the presence of strong interference and dense emitter environments. As mentioned previously, the principal design objectives of the MFEW program were to reduce technical, cost, and schedule risk for the development and production of a next-generation ship's EW system. To accomplish this, the team worked with Navy operators to refine EW requirements and to develop the EW concept of operations, threat characteristics, and scenarios. The RFI/EMI environment and ship signature requirements of the DDG-1000 class were significantly different than in previous ship classes. The project was directed to employ Modular Open Systems Approach (MOSA) principles to provide a total fleet solution and to simplify future technology insertions. The design was to also provide for growth to a multifunction system, potentially including high-gain, high-sensing systems; electronic attack capabilities; frequency extension; and electro-optic and infrared (EOIR) systems and paths to add communications and radar functions. The project leveraged systems engineering, software, and hardware developed on the SLQ-32, the Advanced Integrated Electronic Warfare System (AIEWS); the SEWIP; and the EA-6B and EA-18G programs. It also used existing EW processing from SEWIP and an overwater, direction-finding solution proven in the AIEWS.

The MFEW system was further designed to use a wide variety of antenna/aperture types as required by the ship configuration and functional capability and employs a wideband, distributed radio frequency (RF)-to-intermediate frequency (IF) converter with multiple RFI mitigation features. Moreover, MFEW uses a common digital receiver/exciter building block that supports acquisition; direction finding; modulation on pulse; low probability of intercept waveforms; built-in-test/calibration; and electronic attack. Additionally, MFEW employs open, industry standards at all single replaceable unit (SRU) interfaces. Commercial off-the-shelf (COTS) hardware and open software are used for all pulse, emitter, and related processing.

The schedule for the MFEW project was very aggressive. It began with a kickoff in October 2005, followed very quickly with a system design review in December 2005, a preliminary design review in March 2006, and a critical design review in June 2006. Factory acceptance testing began in December 2006 with integration of the system at NRL's Chesapeake Beach Test Bed in late Summer 2007 and demonstration in December 2007. The compact 2-year schedule allowed for a ship demonstration during the Rim of the Pacific Exercise (RIMPAC) in the summer of 2008. The final report, dated August 2009, and analysis data is available from the Naval Research Laboratory Radar Division.

In all, the MFEW Program met its goals to develop a MFEW ADM for the DDG-1000 ship class that demonstrated key electronic surveillance capabilities of high probability of intercept, precision direction finding, and specific emitter identification. These results will help ensure that future Navy ship classes and warfighters will have enhanced EW capabilities necessary to identify and defeat adversary capabilities.

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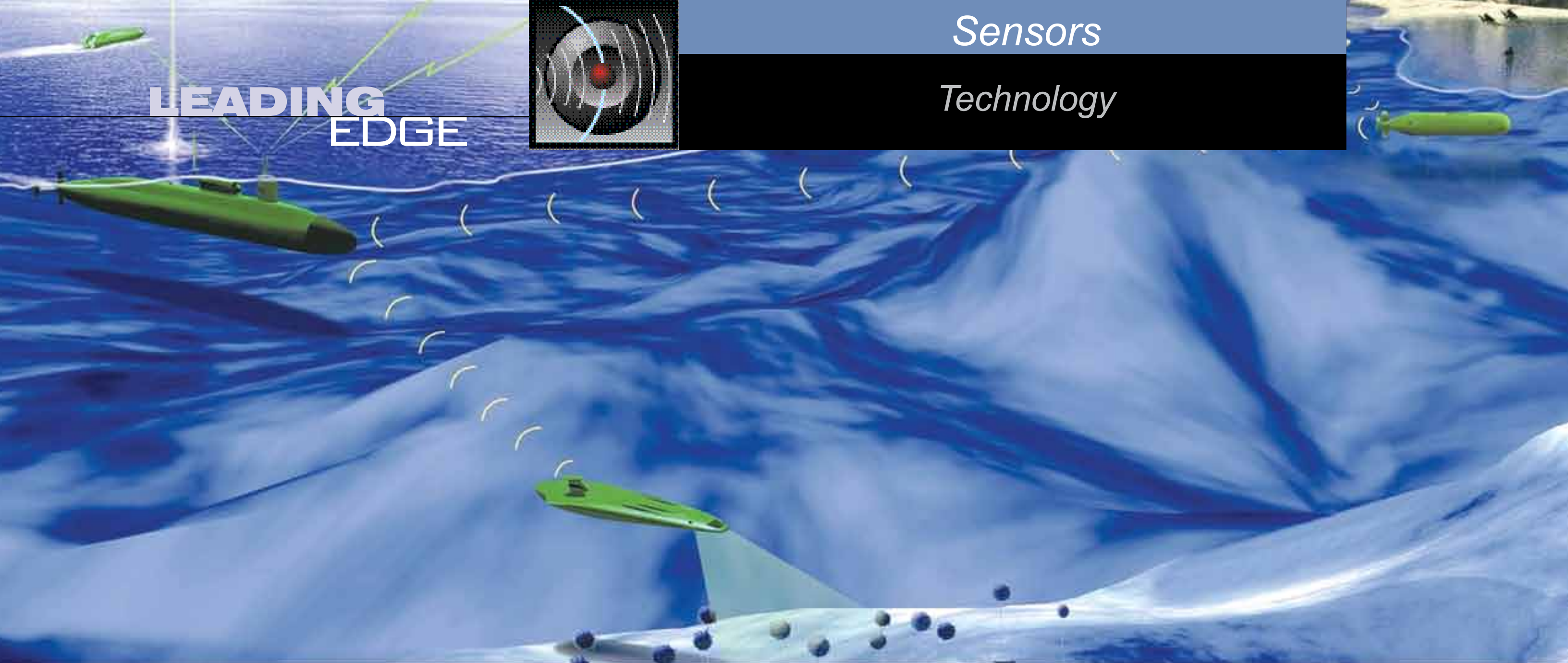

Innovation Strategies for Undersea Sensing

By Tom Choinski

Five years ago, the Sensors and Sonar Systems Department of the Naval Undersea Warfare Center (NUWC) set off on an organizational experiment. The department's experiment was the creation of a division consisting of over 60 scientists and engineers whose sole purpose was innovation. The organization was named the Emergent and Transformational Systems Division, and their mission was to address emerging fleet needs by developing and transitioning radically innovative technologies to the fleet. The technologies primarily focused on undersea sensing and undersea warfare.

Other divisions in the department and at NUWC also innovate. What made this division unique was that its innovation couldn't be incremental or along traditional product lines. The innovation had to be radical and game-changing. The focus was to work on concepts that could potentially change the calculus of undersea warfare from a sensing perspective. Insofar as the division is still improving and growing its ability to innovate, a lot can be learned from its experiences over the last 5 years.

Innovation is important because advancements of all kinds are taking place at a rapid pace due to globalization. Globalization enables everyone to have equal access to technology on a level playing field. Global leadership will be gained by those organizations that can transform their resources rapidly to meet emerging needs and requirements. The Navy has emphasized the importance of innovation through several organizations such as the Chief of Naval Operation's Strategic Studies Group (CNO SSG), the Naval Warfare Development Command (NWDC), the Office of Naval Research (ONR), and the Warfare Centers. The ability to transform resources rapidly has also been identified as a key capability for future success by organizations such as the Lawrence Livermore National Laboratory and the Central Intelligence Agency (CIA).

Warriors must have a need and the desire to adopt the concepts and technologies that are developed. The technologies must also fit within the context of existing doctrine, organization, training, materiel, leadership, personnel, and facilities (DOTMLPF) for success. In addition, new concepts must support requirements, operational concepts, and acquisition planning.

The Emergent and Transformational Systems Division achieved success in innovation through a strategy that encompassed education, invention, prototyping, at-sea experimentation, analysis, collaboration, innovation cells, and adoption by the warrior. Each of these components of the strategy is subsequently discussed.

Education

The division's education started with the Innovation Strategies Course offered through NUWC University. The course focused on the innovation equation:

Innovation = f(Invention, Commercialization, Diffusion)

People often confuse innovation with ideation or creativity. The course took as its premise that innovation is a function of invention, militarization, and the diffusion or the adoption of the idea by the warrior. Consequently, a great technological idea that is not adopted by the warrior would not qualify as an innovation under this definition. The course was a 1-day course developed from extensive research compiled by the author, as well as many people at NUWC who provided information from related experiences and research on the topic. The extensive bibliography for the course—which included articles, books, and videos—was donated to NUWC's Technical Library so that everyone at NUWC could benefit from this information. Figure 1 shows examples of new additions to NUWC's library resources on innovation.

Figure 1. NUWC Library Resources on Innovation

Invention

Invention leveraged the talented and experienced technical staff of the division. Many new products were invented, developed, and prototyped through support provided by NUWC's bid and proposal program; ONR; Naval Sea Systems Command (NAVSEA); and Program Executive Office, Naval Mine and Anti-Submarine Warfare Command (PEO-IWS5A). These organizations also supported work in the prototyping, experimentation, and analysis phases of innovation. Figures 2 through 5 show one idea conceived and developed under NUWC's bid and proposal program. The idea was based on undersea distributed networked sensing (UDNS) techniques using small or microsized unmanned surface vessels (USVs) that could be controlled, navigated, and tracked through Web-based tools. The micro USVs could be used to provide inexpensive, expendable, mobile undersea sensors for riverine applications or to investigate potential undersea targets at low cost. Figure 6 shows another device that provides a Web-based buoyant radio frequency (RF) location function that could be used to locate assets that need to be recovered after undersea experimentation.

Prototyping

Prototyping was critical to the development of new technology concepts. Existing systems tended to offer the best opportunities for prototypes because ideas could be developed quicker by modifying those systems. Moreover, modified systems had greater potential for transition into an acquisition pipeline and would be adopted by the warrior faster if the existing system was already proven and accepted by the fleet. Figure 7 shows nontraditional undersea warfare concept prototypes developed from standard mobile target devices called Expendable Mobile Antisubmarine Warfare Training Targets (EMATTs). These prototypes were designed, built, and used during at-sea experiments. Modifying existing systems enabled rapid prototyping and at-sea experimentation in an expeditious manner.

At-Sea Experimentation

At-sea experimentation by the fleet is essential to any technical innovation process. Experimentation enables the fleet to take new technology concepts and judge the values and merits of the technologies for themselves. Technology concepts that offer potential value to the fleet can be shaped and modified into a form that will be useful to the fleet in the future. In addition, at-sea experimentation enables the fleet to develop and mature doctrine and operational concepts, as well as tactics, techniques, and procedures for

Figure 2. UDNS Micro USV

Figure 3. UDNS Micro USV Compared to Spartan USV

Figure 4. Video Image for UDNS Micro USV

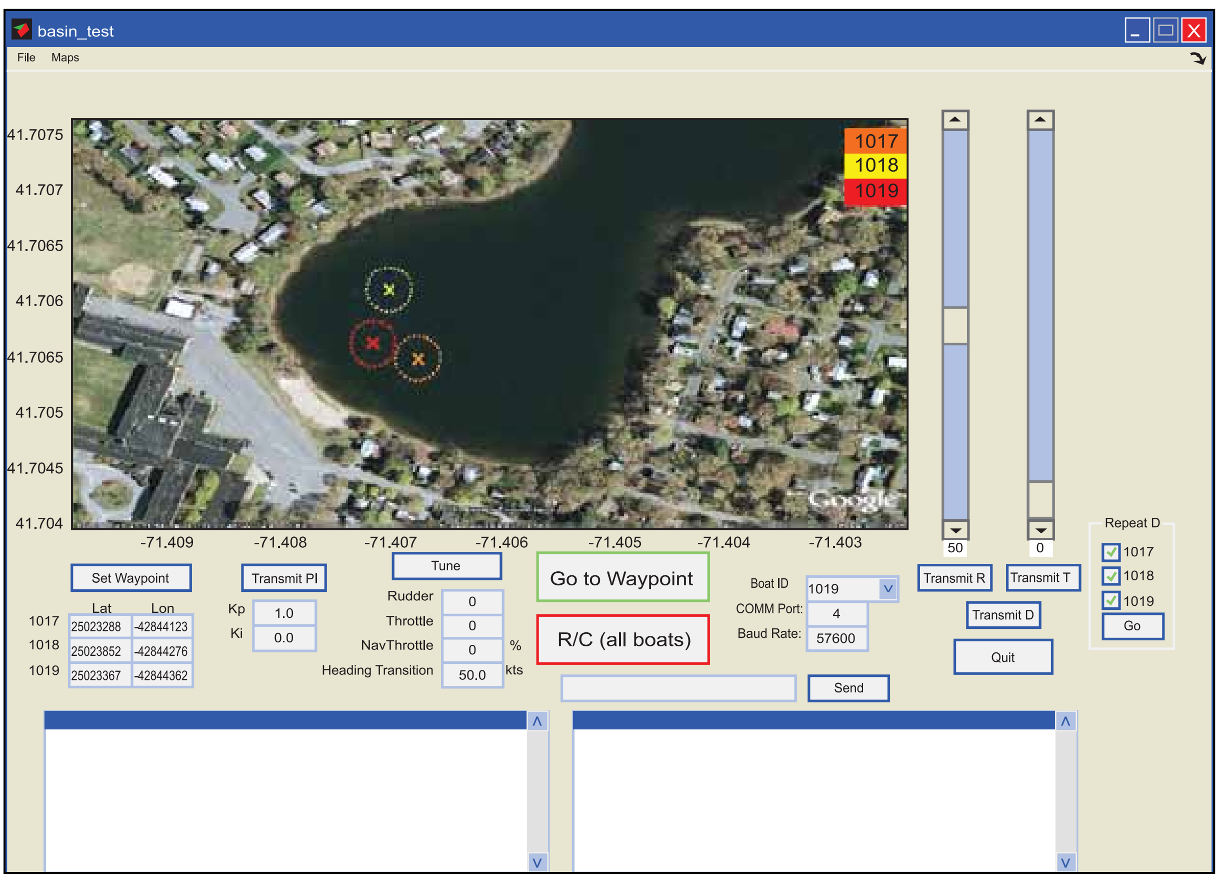

Figure 5. COTS Web-Based Control for UDNS Micro USV

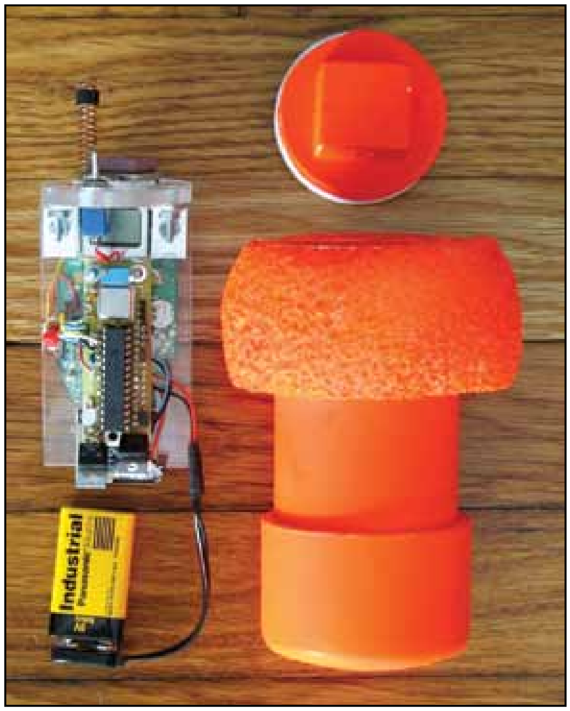

Figure 6. Web-Based Buoyant RF Locator for Experimentation

Figure 7. Nontraditional Undersea Warfare Prototypes for At-Sea Experimentation

new technology. Through experimentation, technology and fleet concepts are developed in parallel to expedite the innovation process. The engineers in the division participated in at-sea experimentation, often during adverse weather conditions, to collect the data necessary for assessment. Figure 8 shows one of the ships involved in experimentation during TASWEX-04. The experiment was conducted immediately following a typhoon.

Figure 8. Image of Waves Crashing on Deck of Ship During TASWEX-04 Immediately Following a Typhoon

Analysis

Analysis is critical throughout the invention, militarization, and diffusion phases of innovation. For acoustics, signal strength is one characteristic that is often analyzed for new concepts. Figure 9 shows the results from a preliminary target strength concept for an innovative, acoustic shadow project funded with internal NUWC resources. This concept leveraged background noise characteristics to enhance the detection and localization of underwater objects such as submarines. The analysis shown in Figure 9 demonstrates how the aspect dependencies could be assessed for target strength of a notional submarine. In addition to using modeling and simulation tools, the analysis also included operational assessments. Experience gained and relationships developed between scientists and engineers and the fleet from at-sea experimentation contributes to successful tactical and operational performance assessments of new concepts and technologies. Working with the fleet to determine the operational value of new technologies is important for the adoption and acceptance of innovative technologies.

Collaboration

Early fleet experimentation with developmental systems facilitates the adoption of innova-

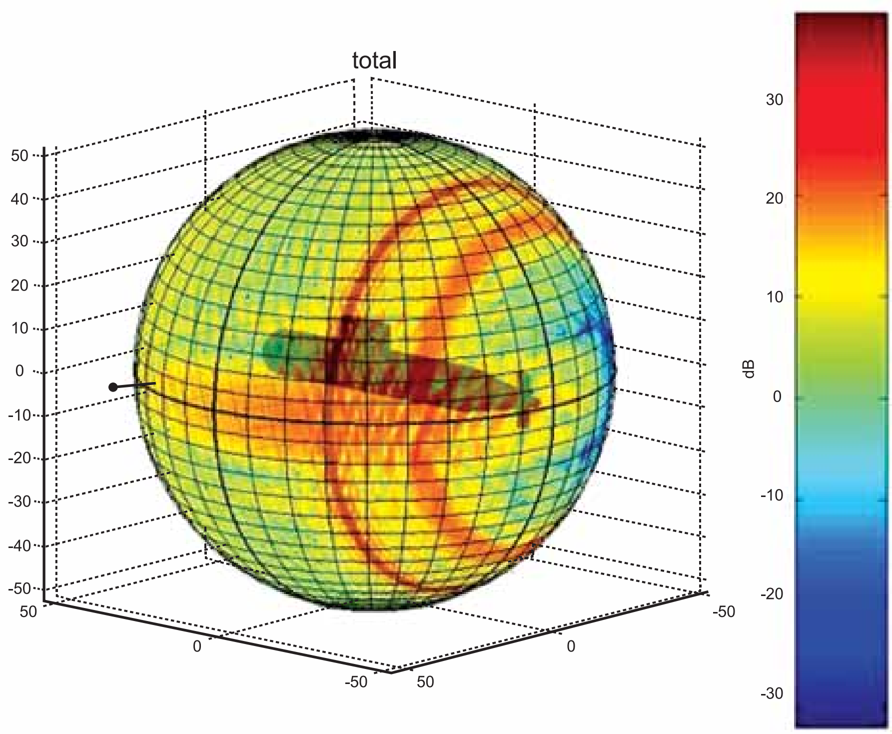

Figure 9. Target Strength Modeling for Acoustic Shadow

tive technologies through collaboration among the technology developers, the end users in the fleet, the acquisition community, and the engineers of the existing systems. It facilitates communication and sets the stage for observation by the end user (fleet operators, officers, and commanders) concerning the effectiveness, compatibility to tactics and fleet systems, reliability, and applicability to their operational requirements. At-sea experimentation of new technologies and concepts allows the fleet to make the final judgment and comparison of the performance of existing systems. Figure 10 illustrates recent examples of early fleet experimentation of undersea systems. The developmental systems were used along with existing fleet systems and as part of a typical integrated antisubmarine warfare (ASW) prosecution involving an ASW commander, a destroyer squadron, and ASW aircraft. The fleet was proactively involved in the tactical employment of the developmental system offering hands-on lessons learned.

Collaboration occurs throughout the innovation process, not just in experimentation. Practically all of the division's success stories involved collaboration with other organizations; some within NUWC, some within NAVSEA, others with the Department of Defense (DoD) (the services), industry, and international partnerships. The Naval Surface Warfare Center (NSWC) Carderock, NSWC Dahlgren, the Air Force, and The Technical Cooperation Program (TTCP) are a few examples of the collaborations that have been integral to the division's success. NUWC has collaborated with NSWC in several technology areas. The division leveraged RF radar expertise from NSWC Dahlgren, as well as tow-body design capabilities, test facilities, and marine architect and design expertise from NSWC Carderock. These collaborative initiatives reduced cost and development time while ensuring a higher quality product. Foreign collaboration was built through TTCP and through partnerships among Australia, Canada, New Zealand, Great Britain, and the United States.

Innovation Cells

Innovation cells are another venue where collaboration is important. They help to facilitate analysis. For example, one innovation cell focused on issues associated with at-sea experimentation and utilized the research on the diffusion of innovation. The results of the innovation cell shown in Table 1 illustrate how the 11 attributes of innovation were assessed.

A discussion on each of the 11 attributes is beyond the scope of this article, but note that the effort uncovered observability as the crucial attribute to the undersea experimentation process. Each of the 11 attributes of the diffusion of innovation was ranked on a scale from 1 to 7, where 1 indicated a favorable rating, and 7 indicated a poor rating. Reliability, radicalness, observability, and economic advantage received poor ratings. Reliability and economic advantage were rated poor not because of the performance of the system, but because of a lack of communication of the performance of the system to the fleet. By changing the way we communicated the reliability performance and economic advantage of this system, we were able to improve these ratings. The rating for radicalness could not be addressed because of the fundamental nature of this innovative concept.

However, the rating for observability uncovered a fundamental issue with new undersea sensing concepts. Observability is the degree to which the results of an innovation are communicated as being visible to others. The observability attribute offers unique challenges for the undersea sensing environment simply because there is very little visibility under the sea. Data is collected during undersea experiments and often requires months of analysis in the laboratory to assess performance. This is especially important because the participants from the experiment are often long dispersed by the time the analysis results are reported out in detail. The innovation cell identified ways to improve observability during undersea sensing experiments. These improvements included:

- Planning for Experimentation
  - Empower riders with a priori knowledge of scenarios
  - Plan to collect mission-based metrics
  - Disseminate experiment plan to appropriate players
  - Develop a communication plan before the experiment
- Communication During Experimentation
  - Leverage low-bandwidth chat
  - Improve platform tracking with the ASW Tactical Assessment System (ATAS)
  - Integrate overhead assets; e.g., Global Hawk
  - Use acoustic communications (ACOMMS) for in situ submarine communications
  - Use the submarine as the hub for analysis
- Analysis After Experimentation
  - Capture warrior observations via the Web
  - Conduct collaborative analyses
  - Disseminate results electronically to solicit feedback

Figure 10. Collaboration Through Experimentation

Table 1. Innovation Cell Results for Undersea Experimentation

Attribute	Intent or Perception (1–7)	Comment
Applicability	1	Highly applicable, high utility
Reliability	6	Not strongly communicated
Compatibility	1	Compatible with existing concepts of operation
Divisibility	2	Alternate options communicated
Radicalness (reverse coded)	5	Communicated effort as being different
Complexity (reverse coded)	2	Not highly complex (context dependent)
Trialability	1	Use of systems in experimentation strongly emphasized
Observability	4	Not strongly communicated
Effectiveness	2	Analysis used to determine performance
Commutuality	1	Complementary nature strongly articulated
Economic Advantage	5	Not strongly communicated
Total	30	
Avg	2.73	

Adoption

The diffusion of innovation, including adoption by the warrior, remains as one of the greatest challenges in the innovation process to date. Figure 11 provides a notional depiction of how the innovation and militarization pieces of the innovation equation have been expedited since the Cold War. The advent of commercial off-the-shelf (COTS) equipment and programs, like the Acoustic Rapid COTS Insertion (ARCI) Program, has made great strides in shrinking the invention and militarization phases drastically. However, when radical—rather than incremental—innovations are needed, the diffusion phase may offer the greatest opportunity for improvement.

The Emergent and Transformation Systems Division has been recognized for its achievements and continues to improve upon the strategy that success in innovation can be achieved through education, invention, prototyping, at-sea experimentation, analysis, collaboration, innovation cells, and adoption by the warrior. The division's recognition includes the Warfare Center 2008 Innovation Award; the PEO-IWS 2007 Award for Innovation; the National Society of Professional Engineer's Top 10 Federal Engineer of the Year Award; the Rhode Island Federal Employee of the Year Award; and recently, recognition in USA Today's announcement for New Faces in Engineering.

By leveraging existing systems and COTS equipment, the invention and militarization phases experience rapid turnaround. Striving to ensure that new concepts align within the context of existing DOTMLPF improves the diffusion phase and maintains the focus on requirements, operational concepts, and integration into acquisition planning. Improving the observability of undersea warfare experiments also helps to improve the diffusion phase of innovation, which more quickly arms warfighters with vastly improved capabilities.

Acknowledgment

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Figure 11. The Diffusion of Innovation Challenge