Aegis Anti-Air Warfare Tactical Decision Aids

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APL has been developing shipboard tactical decision aids since 1986 to address the needs of the Aegis warfighter. These efforts have applied a legacy of anti-air warfare experience since the 1970s through radar simulation, propagation analysis, environmental assessment, field testing, and U.S. Navy exercise support. The Laboratory has delivered several capabilities to the operational Navy. Central to these successes was the development, starting in 1993, of a prototype system known as SEAWASP for defining requirements and demonstrating capabilities. Lessons learned from the prototype allowed deployment of a limited-capability rapid technology-insertion effort across the Aegis Fleet. In parallel, SEAWASP development continued, culminating in long-term installations of SEAWASP operational prototypes on USS *Anzio* and USS *Cape St. George*, through four deployments from 1996 to 2001. Currently, SEAWASP's Environmental Assessment System is being transitioned to production as a major component of SMOOS(R)—the Navy's Shipboard Meteorological and Oceanographic Observation System (Replacement)—and the Moriah sensor system to support N096 requirements.

INTRODUCTION

The interaction of the ocean and atmosphere, particularly in the vicinity of land, can create a dynamic environment that changes as a function of time and space in ways that significantly impact ship systems relying on radio-frequency propagation. Impacts on the tactical use of combat systems by the warfighter can likewise be complex or even intractable without knowledge of the environment. In particular, this can be true of Aegis low-elevation combat system performance. This interaction affects radar configuration, ship stationing, situational awareness, and missile doctrine selection. Tactical decision aids (TDAs), however, can be used to compensate for and even exploit the environment to maintain self-defense and area defense performance.

APL has been involved in the development of shipboard TDAs to address the needs of AN/SPY-1 radar operators and Aegis command personnel since 1986. This technology has resulted from a legacy of anti-air warfare (AAW) support since the 1970s through radar simulation, propagation analysis, environmental assessment, field testing, and U.S. Navy exercise support. Early efforts to include realistic environmental characterizations in Aegis shipboard performance assessments while at sea began with the System Performance and

Response (SPAR) experiment in 1988. These efforts led to the development in 1993 of an at-sea test platform, known as the Shipboard Environmental Assessment/ Weapon System Performance (SEAWASP) System, for defining requirements and demonstrating capabilities. From 1996 to 2001, long-term installations of operational SEAWASP prototypes have been fielded on USS *Anzio* (CG 68) and USS *Cape St. George* (CG 71), refining the concept of the Aegis tactical assessment capability through four deployments. The system has been procedurally integrated into routine AAW self-defense operations as well. In parallel, APL supported a rapid technology-insertion effort to address immediate operational needs via the Aegis Core Tactics Tactical Memorandum (TACMEMO) starting in 1995.

Currently, SEAWASP's Environmental Assessment System (EAS) is being transitioned to production as a major component of the Navy's Shipboard Meteorological and Oceanographic Observation System (Replacement) called SMOOS(R) and the Moriah sensor system to support the Office of the Chief of Naval Operations N096 meteorology and oceanography (METOC) requirements. With the inclusion of an optional rocketsonde system, SMOOS(R)/Moriah also supports the near-term Aegis METOC requirements for tactical ship self-defense assessments; however, there is no funded program to field such a capability. Both SEAWASP-equipped ships have enthusiastically endorsed consideration of the *complete* SEAWASP TDA—including SMOOS(R), rocketsondes, and combat system performance assessment capability—in future Aegis baselines.

A companion article by Rottier et al., this issue, describes the impact of the environment on radar, electronic support measures, communication, and weapon systems. It also describes a wide array of meteorological sensors and processing techniques developed to characterize the environment in support of combat system analysis, Navy exercises, and field tests since the early 1980s. A second companion article by Newkirk et al. describes the development, verification and validation, and recent advances to the Tropospheric Electromagnetic Parabolic Equation Routine (TEMPER) radio-frequency propagation program. TEMPER has been developed over the years to take advantage of realistic environmental characterizations and to enable high-fidelity *in situ* propagation assessments in support of combat system performance evaluation. A historical perspective on TEMPER, its relation to other propagation models, and its relevance to the Navy (e.g., shipboard decision aids) is provided in Ref. 1.

This present article describes operational and prototype TDAs that leverage the environmental and propagation assessment capabilities noted above to provide the Aegis warfighter with near-real-time assessments of combat system capabilities and limitations.

ANTI-AIR WARFARE SUPPORT, 1970s and 1980s

In the 1970s, APL helped the Navy define the concept of an integrated combat system with a multifunctional phased array radar as the primary sensor. As part of this effort, the Laboratory developed a simulation of the first AN/SPY-1 Engineering Development Model, installed on the test ship USS *Norton Sound* (AVM 1) in 1973. As the need to understand combat system performance for an automatic transition-to-track system emerged, a radar "firm track" definition and modeling methodology was developed. The initial APL AN/SPY-1 FirmTrack simulation was constructed and supported studies of Aegis Weapon System performance. Support for Engineering Development Model-3 and Standard Missile (SM)-2 firings on USS *Norton Sound* included AN/SPY-1 FirmTrack analysis.

In 1982, the Aegis Program Office began supporting APL development of advanced low-elevation propagation models in response to a growing recognition of the impact of the atmosphere on horizon-search radar functions and low-elevation engagements. This work focused on developing a new generation of numerically efficient propagation algorithms, originally developed for acoustic propagation in the sea, which showed promise for application to the problem of electromagnetic propagation through the atmosphere. APL's Electromagnetic Parabolic Equation (EMPE) model was developed originally in the Submarine Technology Department[2] for application to AAW-related issues. By 1985, the FirmTrack simulation could accept EMPE propagation factors using hypothetical atmospheric refractivity profiles that varied realistically in altitude and range.

Independently, throughout the 1970s, APL's Space and Submarine Technology departments developed novel instrumentation and techniques for measuring environmental parameters that impact low-elevation microwave propagation. By the early 1980s, interaction between the Space and Fleet Systems departments led to the development of a helicopter-based system to characterize realistic variations in atmospheric refractivity.[3] The system was first used in October 1984 in support of a joint U.S. Navy/Federal Republic of Germany Navy (USN/FGN) missile firing exercise in the Puerto Rico Operations Area. By applying refractivity characterizations from the helicopter system to EMPE propagation calculations for the AN/SPG-55B Terrier fire control radar at C- and X-band frequencies, modeled and measured signal levels were compared to evaluate the propagation assessment procedure. Excellent agreement between the two provided the motivation to apply the same procedure to address an issue that was emerging from live firing tests of the new Aegis combat system, i.e., whether variations in observed performance

were due to system problems or whether they could be explained by variations in the environment.

To test the source of these variations, the environmental helicopter system measured atmospheric refractivity in conjunction with a live firing exercise during a 1985 Combat Systems Ship Qualification Trial (CSSQT) for USS *Vincennes* (CG 49). Excellent agreement between actual and computed firm track ranges based on *in situ* propagation assessments led to APL environmental support for subsequent CSSQTs and USN/FGN missile exercises. Consistent agreement between the firm track ranges was observed for all cases where the environmental measurements were collected in a timely manner relative to the test event. Figure 1 illustrates both the variations in performance due to the environment and the ability to reconstruct performance given sufficient information about the environment. The blue bars indicate relative range at which a test target was transitioned into track by the AN/SPY-1 radar for 20 Navy live firing exercises. Variations in performance by a factor of 3 to 4 due to the environment can be seen. Firm track ranges from postexercise analysis for the 10 cases where adequate environmental measurements were obtained are shown in red.

Live firing test results added momentum to a growing realization that the environment impacted system performance. Helicopter-based environmental characterization soon became a requirement for Aegis CSSQTs. By 1993, APL's environmental helicopter capability was transitioned to the Naval Air Warfare Center Weapons Division in Point Mugu, California. In addition, insights into the effects of the environment led to U.S. Navy support for a series of APL propagation experiments at

NASA's Wallops Flight Facility, Virginia, that lasted from 1985 to 1990. These tests further validated modeling procedures and explored issues such as the consequences of propagation on clutter and on monopulse elevation angle errors. Examples of comparisons between measured and modeled signal levels from this period are given in Newkirk et al., this issue, and in Ref. 4.

During this same period, APL supported a wide variety of field tests and analysis efforts for many other programs, including those discussed by Rottier et al. The result of these activities was the development of an array of novel METOC instrumentation as well as algorithms. These algorithms were used to assimilate measurements into characterizations of atmospheric refractivity and the sea surface for the EMPE propagation model, and were also applied to a variety of combat system simulations. Also during this period, the Fleet Systems Department developed a version of EMPE which was renamed TEMPER. Propagation experiments at NASA/Wallops Flight Facility have continued to the present, often in cooperation with Navy laboratories such as the Naval Surface Warfare Center/Dahlgren Division (NSWC/DD), Naval Postgraduate School (NPS), Naval Research Laboratory (NRL), and Space and Naval Warfare Systems Command (SPAWAR) Systems Center/San Diego (SSC/SD).

EARLY PROTOTYPE AEGIS TACTICAL DECISION AIDS, 1980s and 1990s

The Aegis community had concluded that accurate combat system performance assessments were valuable to the Aegis warfighter in terms of ship stationing, adapting radar configuration appropriately to the environment, and maintaining awareness of self-defense capabilities and limitations. The accuracy of APL's postexercise analysis capability in support of Aegis live firing tests was demonstrated at sea in 1988 during SPAR experiments on a deploying Aegis cruiser, USS *Leyte Gulf* (CG 55).[5,6] SPAR demonstrated the concept of individual ship and battle group AAW capability assessment against specific threats based on AN/SPY-1 detection range, command and decision system response, weapons engagement response, and missile performance based on rocketsonde[3] refractivity profiles and EMPE propagation assessments.

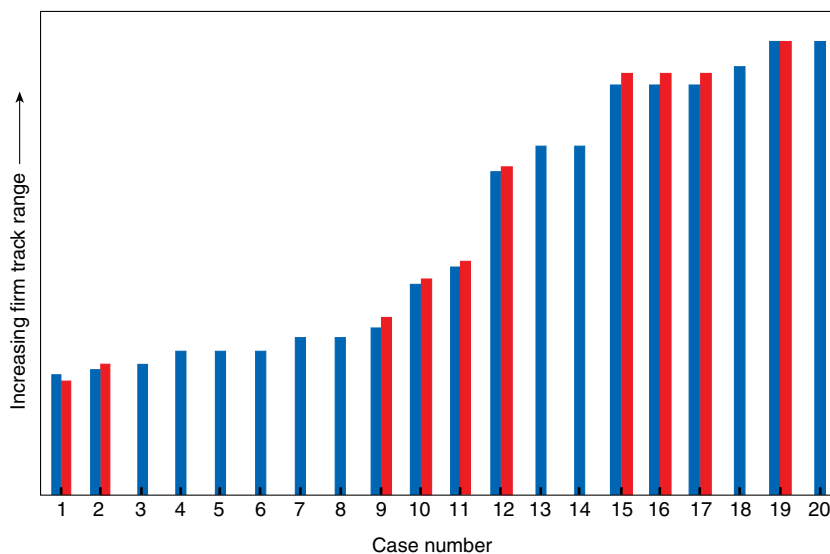In the early 1990s, insights about the impact of the environment on Aegis performance gained from

Figure 1. Twenty cases showing variation in actual AN/SPY-1 performance for littoral environments are shown in blue (actual firm track range). Cases where timely helicopter and/or rocketsonde measurements supported postexercise AN/SPY-1 performance analysis are shown in red (simulated firm track range).

CSSQTs led to the renewed interest of the Aegis Program Office, PMS-400B, in an operational performance assessment capability to leverage the SPAR demonstration. The need was underscored by projections that anti-ship missile threats would increase in speed and decrease in detectability, further stressing combat system reaction times. The aims of such a capability would be to help Radar System Controllers (RSCs) on Aegis ships optimize AN/SPY-1 performance under prevailing environmental conditions and to raise situational awareness of self-defense capabilities and limitations at the command level. System requirements and decision aid concepts were discussed in several meetings of the Aegis Environmental Working Group from 1992 to 1994.

Conduct of field tests and Fleet exercises provided APL with an initial indication of data resolution and accuracy requirements for characterizing the environment. These requirements were more stringent than previous Navy low-altitude requirements. To further define the requirements and explore how realistic they were for a shipboard environment, APL's Fleet Systems Department began adapting a subset of its test-support METOC instrumentation into an integrated environmental characterization system—the EAS—that became appropriate for shipboard installation in late 1992.

The Early Environmental Assessment System

The early generation of the EAS characterized atmospheric phenomena local to the ship that impacted AN/SPY-1's tracking performance for low-altitude targets. These phenomena include evaporative ducts, surface-based ducts, subrefraction, and low-altitude elevated ducts (see the boxed insert in Rottier et al., this issue, for a description of these atmospheric refractivity conditions). The EAS measured temperature, humidity, and atmospheric pressure at a 0.5-Hz rate, 6 m above the sea surface, from either of two sets of sensors attached to meteorological ("met") poles, one on the starboard side of the fantail and the other on the port side. The sensor box on the port met pole contained rapid-response temperature and humidity sensors, an anemometer, and an antenna for receiving meteorological telemetry data from rocketsondes and floatsondes. The starboard met pole box contained an anemometer, temperature, pressure, and humidity sensors, as well as a compass and a GPS antenna. Logic in the environmental assessment processor automatically rejected meteorological data that were determined to be contaminated by ship airwake, based on the wind speed and direction from the anemometers, on a sample-by-sample basis. Met masts were used on both the port and starboard sides to increase the range of directions over which data could be accepted. Five minutes of meteorological measurements were averaged and applied to models to compute a refractivity profile for the particular kind of ducting phenomenon known as the evaporative duct. The evaporative duct is due to the change in temperature and humidity in the layer of air immediately above the surface; it may extend up to several tens of meters.

Floatsondes were deployed over the side of the ship and telemetered measurement data to the receive antenna. Surface water temperature as well as air temperature and humidity were measured centimeters above the sea surface. These data were used in an APL-developed experimental evaporative duct model to generate a refractivity profile of the evaporative duct.

Atmospheric refractivity phenomena above the evaporative duct were measured directly using a rocketsonde (Fig. 2). Rocketsondes launched from the ship released a sensor package that descended from about 610 m to the surface. A profile of temperature, pressure, and humidity was telemetered to the receive antenna, used to compute refractivity, and assimilated with evaporative duct profiles to produce a complete characterization of the local refractivity. This refractivity profile was used in the TEMPER propagation program, which displayed contours of propagation factor (relative power) on an altitude-versus-range plot for AN/SPY-1's lowest-elevation beam position. These displays clearly indicated the effect of the environment on the distribution of power and thus on target detectability. Although the process was automated from the acquisition of data through propagation factor calculation and display, this system was operated and maintained by APL engineers.

At-Sea Testing of the Early EAS

The initial operation of the EAS was on USS *Cape St. George* during that ship's first CSSQT in

Figure 2. SEAWASP rocketsonde launch.

September 1993 (Fig. 3). The 13-day underway started from the Roosevelt Roads Naval Station, Puerto Rico, and included a transit up the East Coast and a live firing exercise in the Virginia Capes Operations Area off Virginia's Eastern Shore. Environmental characterizations during the target presentation were used in a postexercise reconstruction to compute firm track ranges. Actual and reconstructed ranges agreed well, particularly in comparison to ranges computed based on a standard atmosphere assumption.

Elements of the system underwent refinement at sea on USS *Cape St. George*, USS *Anzio*, and USS *Kidd* (DDG 993) during the winter and spring of 1993–1994, in part to pursue a build-a-little, test-a-little approach for the EAS and in part to support at-sea Cooperative Engagement Capability (CEC) tests leading to Developmental Test IIA. The EAS was used during CEC testing to evaluate the ability of foreign intelligence ships to intercept CEC data and to support postexercise reconstruction. Results were used in near–real time to successfully predict AN/SPY-1 performance for the first remotely engaged test target. In addition, a postexercise comparison of results from a second EAS installed on a much smaller boat confirmed that hardware and software measures to avoid ship airwake contamination were effective for the cruiser's installation.

To demonstrate that the EAS would meet the needs of the end user—the Aegis warfighter—a second system, the Radar Performance Assessment System (RPAS), was developed starting in mid-1993. The combined system was dubbed the SEAWASP TDA. The end-user for this version of SEAWASP was the AN/SPY-1 RSC. As noted earlier, the RSC is tasked with optimizing the AN/SPY-1 radar for the prevailing environment, with threat information provided by the Tactical Action Officer (TAO). Typically, optimization

Figure 3. Environmental Assessment System starboard meteorological mast (SEAWASP) on USS *Cape St. George* during the first Navy shipboard at-sea test, September 1993. USS *Ticonderoga* is in the background.

means maximizing radar sensitivity to increase firm track range while maintaining an acceptable level of radar loading, given the existing target and clutter environment. Under stressful cases this means maintaining the minimum firm track range required to support a minimum-range SM-2 engagement for selected missile doctrine. Without a means of estimating radar performance, the RSC adjusts sensitivity without knowing the impact on self-defense capability.

The process recommended to AN/SPY-1 RSCs for setting up the radar in the Aegis Core Tactics TAC-MEMO generally attempts to maximize performance in a prioritized threat sector and strike a balance between radar sensitivity and search rates (search frame times) throughout the search volume. For low-elevation threats, the RSC is asked to determine the radar sensitivity required for the minimum required track initiation range to support a missile engagement. To quantitatively determine this, the radar operator requires a TDA that accounts for environmental effects. The initial SEAWASP prototype TDA was designed to define physical and operational requirements for an Aegis TDA capability to address this need.

THE EARLY SEAWASP SYSTEM

The initial version of SEAWASP combined an evolving EAS with the initial RPAS to automatically produce tactical displays of AN/SPY-1 firm track range appropriate for the RSC's needs. In this system,[7,8] refractivity profiles from the EAS were passed to the RPAS, which applied the TEMPER propagation model for AN/SPY-1 low-elevation parameters. The propagation assessments were used in an AN/SPY-1 firm track simulation to predict the radar performance for manually configurable target parameters. Results were displayed by the Human–Machine Interface (HMI) on a display mounted next to the RSC's console in the ship's Combat Information Center (CIC). The HMI also provided controls for some AN/SPY-1 settings to allow configuration of actual or trial radar doctrine. A suite of programs controlled the flow and maintenance of data and automated the entire procedure—from environmental data acquisition to tactical display updates.

The first SEAWASP EAS mated to the RPAS (Fig. 4) was installed on USS *Port Royal* (CG 73) in Pearl Harbor, Hawaii, in October 1994. The system was tested for 19 days and included a CSSQT conducted off the coast of Kauai by the Pacific Missile Range Facility. SEAWASP predicted and displayed firm track ranges for three test targets prior to their presentation. Agreement between predicted and observed firm track ranges was excellent. USS *Port Royal* requested to keep SEAWASP in anticipation of its upcoming deployment to the Arabian (Persian) Gulf. This request had to be turned down because the system was not yet sufficiently
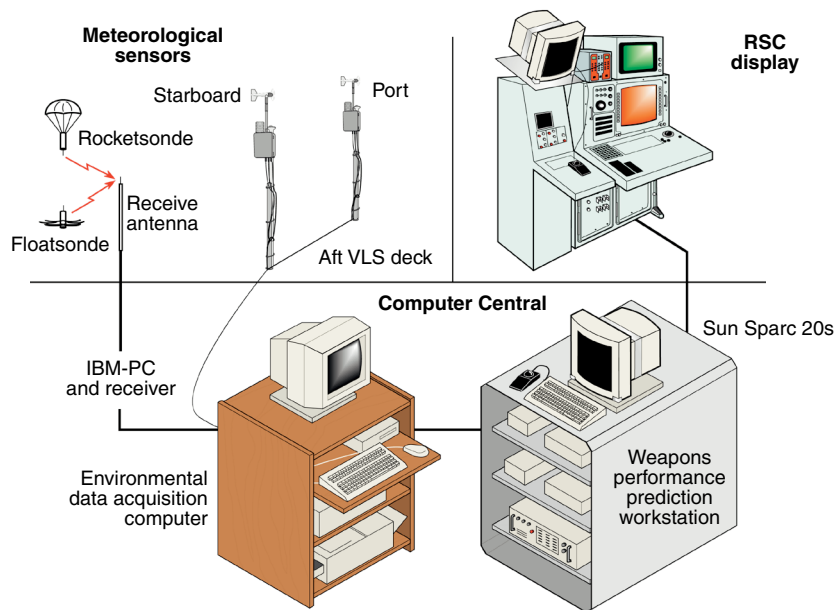
Figure 4. Overview of early SEAWASP installation on USS *Port Royal* in October 1994.

developed for unattended operational use. An opportunity would resurface years later after significant development and evaluation on research vessels, and in-port and at-sea testing on Navy ships, as described below.

The next SEAWASP installation, in February 1995, was on USS *Lake Erie* (CG 70) during deployment in the Arabian Gulf and Gulf of Oman. SEAWASP was evaluated at sea along with several other environmental assessment and TDA prototypes during the SHAREM (Ship ASW Readiness/Effectiveness Measurement) 110A exercise. SEAWASP predictions of AN/SPY-1 performance agreed well with actual performance for several manned aircraft tracking tests.

REFINEMENT OF THE AEGIS TDA CONCEPT AND METOC REQUIREMENTS

In the mid-1990s, the Aegis Program Office developed a concept for an Aegis TDA capability. This was done in an effort to define the relationships among key technologies, focusing on a complete combat system performance assessment capability that would (1) meet the needs of the warfighter based on operational experiences and (2) address specific issues that arose during several CSSQT live missile firing events.[9] This capability relied on assimilating local and remote METOC data to characterize refractivity. Refractivity characterizations would be combined with surface data for propagation and clutter assessments. Results would be fed into radar tracking and SM-2 missile engagement assessments for selected threats. Limitations due to material readiness of the combat system and hardware casualties would also be factored in so as to produce an intuitive display of current combat system performance. This concept is shown in Fig. 5.

APL worked to refine the Aegis METOC requirements relative to this concept based on field tests and SEAWASP experiences. Several empirical and analytic sensitivity studies provided the basis for a set of near- and far-term environmental requirements for an Aegis tactical assessment capability.[10–13] Difficulty in meeting the near-term requirements using boundary layer meteorological models made direct observation of

atmospheric refractivity appear favorable. However, a lack of existing or planned Navy METOC instrumentation to meet the Aegis requirements created a problem. There was an immediate need for METOC sensor support demonstrated in lessons learned from live firing events for an Aegis TDA capability, and there was no near- or far-term plan to fulfill that need. APL was asked to further develop SEAWASP as a risk reduction effort for the Aegis TDA capability, i.e., to focus on demonstrating several technology areas critical to low-altitude self-defense performance assessment. These are indicated within the shaded region of the Aegis TDA concept in Fig. 5.

AN/SPY-1 TDA IN THE AEGIS CORE DOCTRINE (TACTICS) TACMEMO

Immediate Operational Need versus Limited Capability

Because an integrated Aegis performance assessment capability appeared to be years away from Fleet introduction, a rapid technology insertion effort was initiated by the Navy's Surface Warfare Development Group, Little Creek, Virginia, to address the operational needs of Aegis RSCs. At the request of the Aegis Program Office, APL worked with the Aegis operational, training, and R&D communities to develop a simple, stopgap performance assessment capability based only on evaporative ducting.

METOC Instruments and the Evaporative Duct Model

The above-mentioned capability was based on the set of handheld METOC instruments that APL had been using in field tests, e.g., a thermohygrometer (Fig. 6, left) to measure air temperature and humidity and an infrared camera (Fig. 6, right) to measure the sea surface temperature. The Laboratory identified a suitable set of commercial
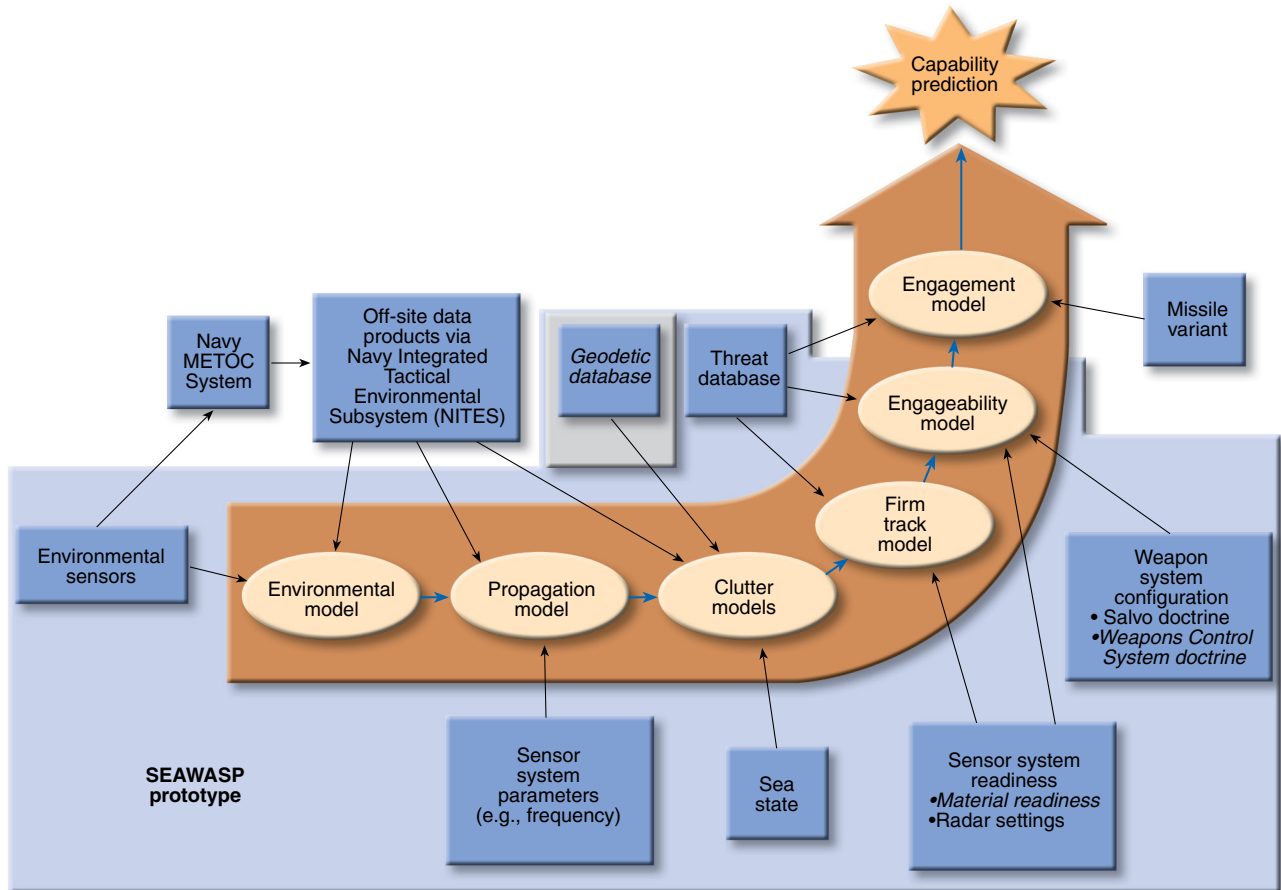
Figure 5. Aegis TDA concept in relation to the SEAWASP operational prototype system installed on USS *Anzio* and USS *Cape St. George*, 1996–2001. (Functionality shown in italics is not fully implemented in SEAWASP.)

Figure 6. An AN/SPY-1 radar technician uses a thermohygrometer (left) to measure air temperature and humidity and an infrared camera (right) to measure sea surface temperature in support of AN/SPY-1 radar performance assessment via tools and guidance provided in TACMEMO.

instruments and developed procedures tailored to evaporative duct characterization in a shipboard environment. Procedures for acclimating the instruments, avoiding ship airwake effects, and averaging multiple measurements were developed to provide appropriate inputs to an evaporative duct model.

Comparisons between actual and computed AN/SPY-1 performance based on METOC data collected from years of live firing tests led to the selection of APL's Constant Virtual Temperature (CVT) evaporative duct model over standard Navy models for this effort. This choice was primarily made because the CVT model consistently resulted in reasonable or slightly low evaporative duct height estimates over a wide range of meteorological conditions, while other models sometimes overestimated

duct height—under some conditions, significantly. The operational and technical community supporting this effort determined that it was operationally better for self-defense applications to underestimate rather than overestimate performance. This conservative tendency better supported the objective of prompting radar operators to increase sensitivity to the maximum extent possible, given radar loading. The CVT evaporative duct model was embedded in a computer program that automatically provided alerts regarding the applicability of the model and some guidance for the radar performance assessment.

Radar Model

The AN/SPY-1 FirmTrack simulation was used to generate a lookup table that is parametric in evaporative duct height, threat characteristics, and radar settings. This table was integrated by NSWC/DD into a program called SPY Sliderule. Sliderule superimposes an AN/SPY-1 sensitivity-versus-range curve on the tabulated performance data to indicate the range at which a radially inbound threat of a specified radar cross section, speed, and cruise altitude would be transitioned into track for given sensitivity settings. It also indicates whether this track initiation range supports various SM-2 engagement doctrines. By 1999, Sliderule and the evaporative duct program, with its CVT model and alerts, were merged into a single application simply called Sliderule.

Operational Guidance

Again, Sliderule only considers variations in evaporative duct height; evaporative duct shape is determined by assuming that the surface layer is neutrally stable. No other refractive conditions—including evaporative duct shapes for unstable and stable surface layers, surface-based ducting, subrefractive conditions, and combinations of these conditions—were explicitly considered in Sliderule. These limitations had to be addressed in operational guidance to ensure appropriate use of this capability.

Guidance procedures developed by APL to address Sliderule limitations were aimed at identifying when evaporative ducting is not the dominant propagation mechanism in the current environment. Instructions were included for using the AN/SPY-1 radar to determine the presence of surface ducting and were complemented by readily observable indications of other atmospheric conditions affecting propagation (e.g., surface fog or a distinct, low-altitude haze layer). This guidance was included in the form of appendices to the Aegis TACMEMO along with background material on refractivity, propagation, and impacts on AN/SPY-1. In addition, a more readily accessible summary of the guidance was incorporated into logs/worksheets completed as part of the procedures to document results and to provide a means of soliciting operator feedback. The entire assessment process was evaluated by APL personnel at sea in support of live-fire missile exercises on Aegis destroyers USS *Ramage* (DDG 61) and USS *Mitscher* (DDG 57). Crew feedback from both ships was used to refine the procedures.

Delivery to the Aegis Fleet

The capability was distributed to the Aegis Fleet via a revision to the Aegis TACMEMO in 1996. APL continues to support updates to the TACMEMO and Sliderule program as well as evaluation of procedures via the logs/worksheets and operational feedback. Currently, the APL evaporative duct program is incorporated in Sliderule. It has also been integrated into the Aegis Display System (ADS) for the Baseline 6 Phase I version of the weapon system by Lockheed Martin Naval Electronic and Surveillance Systems, Moorestown, New Jersey, and is used in conjunction with the AN/SPY-1 sensitivity calculator.

SEAWASP, 1990s and 2000s

Objectives

With all the major technologies for near-real-time, low-elevation AN/SPY-1 radar assessments demonstrated in field tests and engineering models, the next version of SEAWASP was developed as an operational prototype. A major objective of this system was to demonstrate that the EAS could reliably meet the near-term Aegis requirements in an operational environment and do so automatically, with minimal crew maintenance, in the absence of outside assistance from APL engineers. Further, this system was to demonstrate that these environmental assessments could be used to aid the warfighter in making tactical decisions, and thereby define requirements for the operational Aegis tactical assessment capability. A plan was developed to deploy SEAWASP on USS *Anzio* and USS *Cape St. George*. Another APL prototype system, the Combat Display and Control System (CDCS), was also installed on the two ships as a risk reduction effort for Aegis Baseline 6 Phase I. CDCS displays were based on Common Display Kernel (CDK) software, run under the HP-UX operating system on AN/UYQ-70 hardware, and interfaced with the ADS and CEC. Ultimately, SEAWASP leveraged CDCS and CEC to obtain live updates of AN/SPY-1 radar settings and loading parameters to automate radar performance assessments. Over the years, through four deployments and numerous Navy exercises, APL engineers worked at sea alongside many sailors from both ships to refine SEAWASP into a system that is highly automated and procedurally integrated into Aegis tactical decision making.

Initial SEAWASP Operationally Deployable Prototype

References 14–16 describe the SEAWASP operationally deployable prototype system; an overview of the system is shown in Fig. 7. This system leverages heavily off successes of previous versions of SEAWASP. However, numerous engineering hardware and software changes were required to make SEAWASP appropriate for 6-month deployments on operational Navy ships. In addition, displays were completely redesigned based on feedback from the four Aegis cruisers that had seen SEAWASP. These ideas were brought together in a layout similar to, and with functionality that paralleled, the AN/SPY-1B Program Performance Specification for Baseline 5 Phase I, the version of the Aegis Weapon System computer program on USS *Anzio* and USS *Cape St. George*. In doing this, SEAWASP displays were able to successfully leverage crew training, and resulted in operator feedback from RSCs such as, "If you know how to run the radar, you know how to run SEAWASP." The SEAWASP HMI was displayed on an X-Station in the CIC adjacent to the RSC console (Fig. 8). In addition, a threat library was developed from an Office of Naval Intelligence database; this library included real-world low-altitude threats likely to be faced by a battle group on deployment as well as representative U.S.-developed test targets.

The SEAWASP network was connected via the AN/UYQ-70 prototype equipment (CDCS) to the Baseline 5 Phase I ADS and to the Cooperative Engagement Processor (CEP). This allowed SEAWASP to automatically access AN/SPY-1 radar set-up and loading data for the RPAS's radar simulation to assess current radar performance.

Functionally, SEAWASP worked as follows: The RSC selected a threat from the SEAWASP library based on information from the TAO. When the RSC changed radar settings in the course of normal operations, a SEAWASP reassessment was automatically triggered. Within seconds, SEAWASP displays would indicate that a reassessment was in progress for the changed settings and selected threat. A new performance display appeared in the "Current Performance Panel" upon completion of the reassessment. This occurred in several seconds to several tens of seconds, depending on threat, environment, and radar parameters. Performance was shown for all active radar sectors. If the operator was not satisfied with performance for the selected threat, he could load a copy of the current active radar settings to an adjacent "planned performance panel" with a single click, modify trial radar doctrine, and initiate reassessments. The operator could then apply the new planned settings to AN/SPY-1 and monitor SEAWASP's performance assessments to ensure that the desired level of self-defense capability was maintained. This new system was installed on USS *Anzio* and USS *Cape St. George* in the summer of 1996, and was refined through numerous in-port and at-sea tests in close cooperation with the ships.

First Baltic Operations Deployment, 1997

Debriefs following the return of the ships to Norfolk from their participation in Baltic Operations 1997 revealed that the environment had been particularly benign in terms of propagation and ducting; this is typical in higher latitudes. As a result, the crews' general impression of the
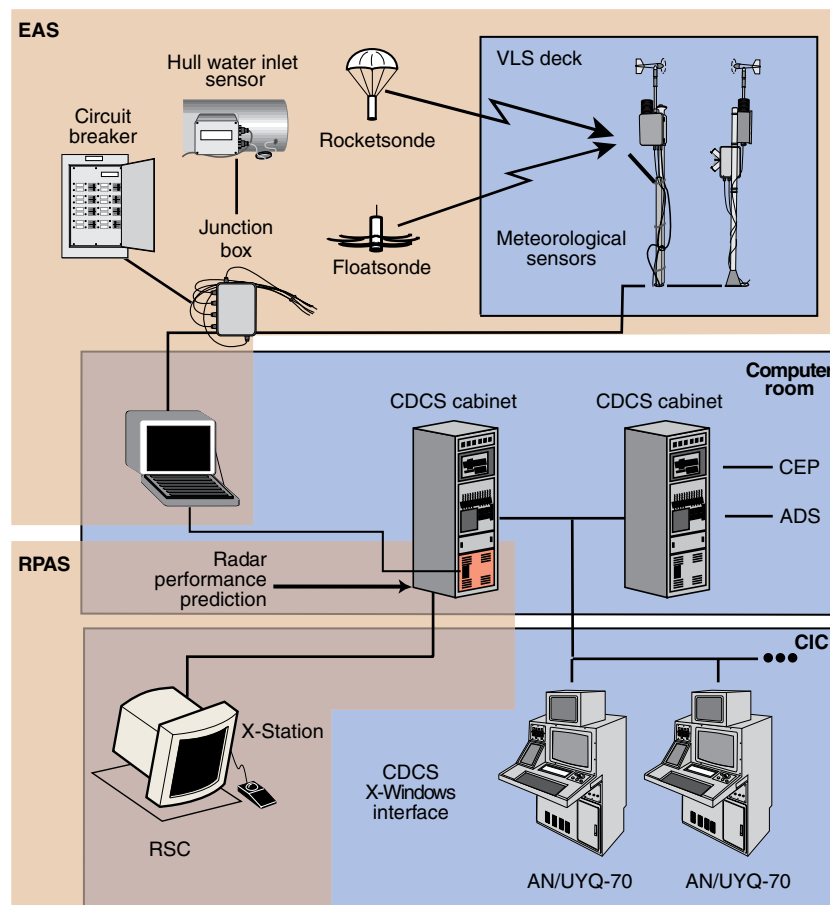

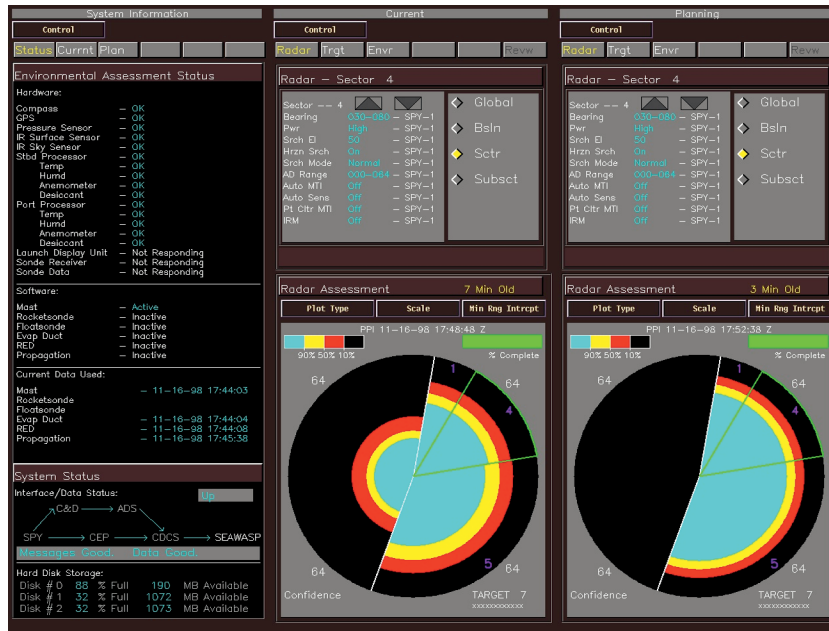**Figure 7.** Overview of SEAWASP installation on USS *Anzio* and USS *Cape St. George*.

Figure 8. SEAWASP display on USS *Anzio* and USS *Cape St. George*.

system was that it was OK but brought them no critical new capability. Several things occurred subsequently to change this impression.

First, at the ships' request, an ability to print SEAWASP displays was implemented. These printouts allowed RSCs to provide daily briefings to the COs regarding AN/SPY-1 performance. Second, the ability to remotely display SEAWASP performance assessments to the AN/UYQ-70 TAO and CO consoles in the CIC was implemented. The specially tailored SEA-WASP Q-70 display facilitated communication with the RSC and the Combat System Controller regarding combat system capabilities and limitations. In addition to the increased visibility that briefing support and command displays provided, the final ingredient that made the value of SEA-WASP clear to the ships was a more dramatic environment. The ships first experienced this during the All Service Combat Identification Evaluation Team (ASCIET) exercise.

ASCIET 1997

In September 1997, USS *Cape St. George* participated in ASCIET in the Gulf of Mexico. A strong surface-based duct was observed for extended periods, which had a significant impact on AN/SPY-1 performance. SEA-WASP's ability to definitively characterize the impact of this environment on system performance using rocketsondes gained high visibility. In January 1998, RADM Huchting, Aegis Program Manager at the time, expressed his "…personal thanks for the excellent technical and operational support provided for … SEAWASP during ASCIET 97."

First Mediterranean Deployment, 1998

While the USS Eisenhower Battle Group (IKEBATGRU) was deployed, an APL team maintained close contact with the cruisers' personnel via unclassified Internet e-mail, classified SIPRNET (Secret Internet Protocol Router Network) e-mail, and INMARSAT (International Maritime Satellite) telephone calls over STU-III lines. These avenues allowed APL engineers to advise, diagnose, and address small problems on several

occasions. Despite minor hardware and software issues, shipboard personnel found SEAWASP to be of great help in understanding prevailing environmental conditions and came to rely on it. One radar operator aboard USS *Cape St. George* during Maritime Interception Operations of Operation Southern Watch in the Arabian Gulf was quoted as saying, "SEAWASP gives us a real tactical advantage. By analyzing the effect of the environment on radar performance, we can adjust radar sensitivity or waveform to ensure that we detect threats while conserving radar resources."

IKEBATGRU returned to Norfolk in December 1998 and was scheduled for redeployment in February 2000. The intervening period provided an opportunity to implement several planned capabilities such as ducted sea clutter and AN/SPY-1 sea clutter processing, as well as the so-called Environmental Expert System (EES). The sea clutter model is an adaptation of the technique described in Refs. 17 and 18; the EES is described in Ref. 19. Improvements were made to each of the models and many of the simulations so as to extend capabilities and improve robustness. Significant hardware improvements were also made to the EAS's external instrumentation to evaluate technology being considered for the Navy's SMOOS(R) being developed by APL, as noted earlier, for PMW-155 and N096.

Second Mediterranean Deployment, 2000

SEAWASP deployed again on USS *Anzio* and USS *Cape St. George* with IKEBATGRU on 18 February 2000. It was used routinely and relied upon extensively during operations off the coast of the former Yugoslavia and in the Arabian Gulf off the coast of Iraq. This most capable and reliable version of SEA-WASP generated considerable support from both ships. SEAWASP

assessments were used to position ships to maintain the desired level of self-defense capability.

Operator feedback from the deployment led to inclusion of a land overlay capability (Fig. 9) in the SEAWASP HMI. This capability silhouettes contours of land over the performance plots to provide a visual indication of range and bearing to land relative to ownship position. The land overlay implementation was evaluated during several postdeployment underways, including CEC developmental tests, technical evaluation, and operational evaluations in 2000 and 2001. It was found to be extremely useful to the RSC for setting radar doctrine to deal with land appropriately in littoral environments. A greatly revised SEAWASP users guide was developed to include all the improvements made since the original version in preparation for the BaltOps 2001 deployment.[20]

Second Baltic Operations Deployment, 2001

The version of SEAWASP that deployed with USS *Anzio* and USS *Cape St. George* was highly reliable and based on mature concepts. Problems with rocketsonde reliability that had been seen on the earlier deployments were gone. Rocketsondes proved not only extremely useful for the information they provided, but also reliable and well suited to operational use. Issues of exposure and water leakage in the externally mounted meteorological instrumentation were examined, causes were identified, and remedies were described for the Navy sponsor for incorporation into the SMOOS(R) design. All internal hardware and software within the ships were reported by the crews to be fully reliable. Soon after the ships returned from BaltOps 2001, SEAWASP was removed in preparation for both ships to undergo

upgrade from Baseline 5.C.5 to Baseline 6 Phase I. SEAWASP is considered by PMS-400B to have successfully accomplished its goals as an operationally deployable prototype. There is no plan to reinstall a prototype SEAWASP capability.

… From the Fleet

The experiences of USS *Anzio* and USS *Cape St. George* with SEAWASP during four deployments resulted in strong official endorsements through 2001. This support was echoed by COMNAVSURFLANT and CINCLANTFLT. Operational support for a SEAWASP capability has led to a request by PEO(TSC) PMS-400B for APL to develop plans for backfitting this capability to existing ships and for incorporating it into plans for future baselines. The system to be considered would resemble SEAWASP's RPAS subsystem and leverage the Navy's SMOOS(R).

SMOOS(R)

In 1996, the Navy was simultaneously considering Operational Requirements Documents (ORDs) for an improved wind sensor system and a replacement for SMOOS. SMOOS(R) was supported by OPNAV N096 and SPAWAR PMW-185, while the wind system was a NAVAIR effort. The ORDs for both systems were combined, and a procurement process was initiated for an integrated system to be known as Moriah.

The SEAWASP EAS was selected as the prototype from which SMOOS(R) would be developed since it had been demonstrated at sea to meet and exceed many of the N096 METOC requirements. In addition, its flexible design facilitated growth to meet remaining needs. Moreover, providing METOC products to support a TDA capability was an N096 objective, and this EAS was demonstrated to support radar performance assessments for the Aegis Fleet via the SEAWASP installations. The realization of a TDA capability, however, would require a SEAWASP/RPAS-like capability that was not part of Moriah, but rather was left for the PMS-400 Program Office and OPNAV N076 to integrate with future weapon system baselines as per the concept depicted in Fig. 5.

Much of the SEAWASP EAS effort with USS *Anzio*, USS *Cape St. George,* and APL's research vessel, R/V *Chessie*, has been oriented toward demonstrating new capabilities and operational suitability for
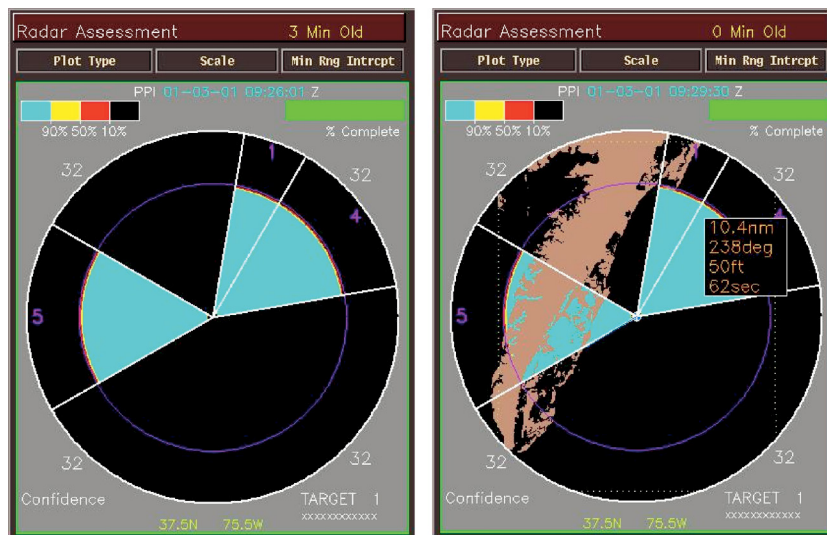

Figure 9. Notional SEAWASP radar assessment windows showing the land overlay capability in the off (left) and on (right) mode. This example is for a ship off the coast of the Virginia Capes. Range, bearing, threat height, and time-till-ownship features are shown in active mode.

SMOOS(R). In parallel, APL has been working with SSC/SD, NPS, and NRL/Monterey on environmental modeling and system development issues to build a production-representative model. This effort to develop the Navy's next generation of automated METOC observation systems has led to a number of improvements over the SEAWASP EAS, which are noted in the following paragraphs.

Evaporative duct profiles are currently calculated in the SEAWASP prototype using APL's CVT model, similar to the model that accompanies the TACMEMO capability described previously. SMOOS(R)/Moriah, however, will use the evaporative duct model being developed by NPS and the Navy community based on a version of the Liu, Katsaros, Businger (LKB) model[21] and recent work by Fairall.[22] Implementation and theoretical issues need to be addressed before this model is appropriate for automated shipboard application. When finalized, an effort will be made to contribute the model to the Oceanographic and Atmospheric Master Library as a Navy standard.

There will be variations in SMOOS(R)'s configuration from one ship class to the next. For example, on Aegis ships SMOOS(R) will have upward- and downward-looking infrared sensors like SEAWASP's (Fig. 10). The former will be used to measure cloud base temperature, and from that estimate the cloud height for certain cloud types. On large ships that have more stringent requirements on cloud base height measurements, however, a laser ceilometer will be incorporated into SMOOS(R)/Moriah. Also, a visibility/precipitation sensor (refractometer) will be incorporated into SMOOS(R) configurations for aircraft carriers.

In addition to sensor and modeling improvements, SEAWASP lessons have resulted in a fundamentally more robust SMOOS(R)/Moriah hardware design that is
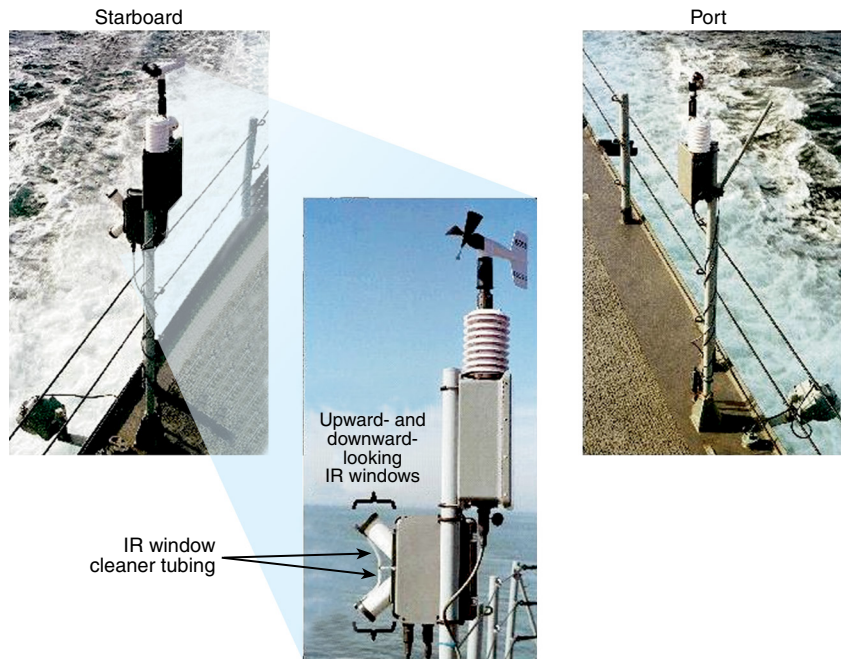

Figure 10. SEAWASP meteorological poles on USS *Anzio.* Upward- and downward-looking infrared windows are seen on the starboard meteorological pole.

easier to maintain, troubleshoot, and repair. For example, electrical improvements and redundancy protect against significant ship power surges and internal failures. Improved connectors and seals guard against moisture penetration for topside equipment. At the board level, increased circuit isolation and filtering provide increased protection from a variety of potential problems. Increased component modularity and interchangeability facilitate repairs. SMOOS(R) will automatically monitor a wide range of system and component voltages/currents as well as communication validity in order to help pinpoint faults quickly. The goal of these improvements is to facilitate maintenance, troubleshooting, and repairs, and to minimize down time.

FUTURE VISION

APL is working with PMS-400B to define the path for transitioning SEAWASP's RPAS capability to backfit into existing Aegis ships and forward fit into new-construction ships to leverage SMOOS(R)/Moriah. The Laboratory is also working with NPS and NRL/Monterey on environmental modeling issues, with SSC/SD and NSWC/DD on propagation and environmental modeling issues, and with Lockheed Martin on deploying this capability in conjunction with a proposed tactical environmental processor (TEP).

Although SEAWASP development to date has focused on an Aegis low-altitude self-defense assessment capability, the embedded models are applicable to more general problems. For example, SEAWASP's FirmTrack model supports the evaluation of crossing and higher-altitude targets. Also, TEMPER is applicable to other microwave radiating systems, including communication systems. These would be natural growth areas for SEAWASP since its software architecture and display capability were developed with these applications in mind. For example, Aegis Mk 99 continuous wave illuminator engagement capabilities and limitations due to environmental effects could be integrated into the engageability assessment. In addition, it has always been a primary goal of the SEAWASP project to include the effects of terrain blockage and land clutter, leveraging emergent capabilities being developed to support analyses in littoral regions.

In addition to Aegis considerations, accurate capability assessments for other combat system elements likewise depend on the environment. For example, CEC's Data Distribution System connectivity, CEC's remote-engagement capability, and the Evolved Seasparrow Missile engagement capability have all been shown during field tests to strongly depend on atmospheric refractivity. Refractivity characterization techniques similar to those automated in SEAWASP have been applied to these systems during Navy exercises. Moreover, each of these systems is recognized to benefit operationally from near-real-time air defense capability assessments.

There are several challenges to developing a near-real-time, self-defense and area defense performance assessment capability. One is the assessment of the environment. While local environmental characterizations currently provided by SEAWASP are sufficient for low-altitude self-defense assessments, it is important to include range-dependent effects on atmospheric refractivity for higher-altitude and area defense assessments. There are several promising technologies that should be explored pursuant to evolving from local environmental characterizations and self-defense assessments toward range-dependent characterizations and area-defense assessments at the level of a battle group. These include rocketsondes, lidars, balloon and aircraft dropsondes, instrumented helicopters, Lockheed Martin's TEP, as well as meteorological models such as NRL/Monterey's Coupled Ocean/Atmospheric Mesoscale Prediction System and Colorado State University's Regional Atmospheric Modeling System.

Another challenge relates to communicating environmental information to locations where it can be processed. Future versions of systems, such as the Navy Integrated Tactical Environmental Subsystem and the Tactical Environmental Data Server, are possible vehicles by which remote METOC sensor measurement and model data might be accessed.

Ultimately the most significant technical challenge may be the automated assimilation of data from a variety of sensors, each with different characteristics, collected in remote locations at different points in time using meteorological models. Results need to be self-consistent regional characterizations of atmospheric refractivity that approach the Aegis far-term requirements mentioned earlier.

Another significant challenge to realizing near-real-time automated battle group air defense assessments in littoral regions is the propagation calculation. To account for realistic terrain effects and three-dimensional variations in atmospheric refractivity, numerous propagation calculations covering large sectors in the direction of a threat for each propagating system may be required. This is largely a computational and data storage issue that will become easier to manage over time as computer technology advances.

If these challenges can be addressed, a common picture of capabilities and limitations across the battle group would allow more coordinated sensor configuration, ship stationing, and weapons doctrine selection by providing a near-real-time check on mission plans. Current programs that would benefit from this capability, in addition to Aegis, include CEC, the Area Air Defense Commander, and the Ship Self-Defense System.

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