APL Environmental Assessment for Navy Anti-Air Warfare

J. Ross Rottier, John R. Rowland, Gerald C. Konstanzer, Julius Goldhirsh, and G. Daniel Dockery

The role of the ocean environment in defense of U.S. Navy ships is amplified when they operate in coastal regions. To address this, APL has developed a unique capability to characterize critical aspects of the ocean environment, particularly those that impact Navy shipboard combat systems through their effects on microwave and infrared propagation. APL produces analysis techniques, instrumentation, models, simulations, and tactical decision aids that support a surface ship's defense against seaskimming missiles. The environmental characterization skill grew out of a need to understand the capabilities and limitations of the Aegis weapon system in the 1980s. Success led to support of a wide variety of Navy and NATO programs for system analysis, at-sea testing, and sensor development. This article provides an overview of the story of environmental assessment and the successes that sprang from the capability to measure and analyze the ocean environment for the Surface Fleet.

INTRODUCTION

In 1814, USS *Constitution*, "Old Ironsides," exploited an enormous bank of marine stratus clouds to evade the British blockade of Boston Harbor. Since then, the Navy has encountered a number of occasions when the ocean environment played an important role in the outcome of a battle. Recall the Marines stranded by the tides at Tarawa, kamikazes using Pacific cloud cover to approach the Fleet, fog during the Battle of the North Atlantic, and the coastal mountain passes that concealed enemy aircraft attacking our ships at Dong Hoi. Despite major advances in naval technology since then, the environment still plays an important role in

ship self-defense and can have a critical impact on reaction time against high-speed, seaskimming missiles.

The Navy Surface Fleet operates within the boundary layer between ocean and atmosphere. The interaction of the two, particularly in the coastal regions, can create a dynamic environment that changes over space and time and can significantly impact ship systems that rely on radio-frequency propagation. The environmental parameters with the greatest impact on radio-frequency systems are atmospheric refraction (see the boxed insert), precipitation, electrical properties of the surface, sea state (roughness of the sea surface), and

ATMOSPHERIC REFRACTION

Atmospheric refraction causes electromagnetic (EM) energy (e.g., light, radar waves) to bend as it propagates. Refraction of EM paths can have a significant impact on signal levels and therefore must be understood.

The refractive bending of EM paths is due to changes in meteorological quantities that affect the refractive index. Water vapor pressure, temperature, and atmospheric pressure impact propagation at radio frequencies up to 100 GHz. Of these, water vapor pressure has the most significant effect on radar and communications. It is calculated from measurements of relative humidity and temperature. Atmospheric refraction can substantially impact EM propagation near the Earth's surface, causing important changes in radar horizon, communication power level, target detection range, and surface clutter.

When humidity at the sea surface decreases rapidly with altitude, energy may be trapped close to the Earth's surface. This "trapping" is frequently referred to as ducting. However, if the relative humidity close to the surface is nearly constant or increases with height, EM energy may be bent upwards and away from the Earth (subrefraction), resulting in decreased radar horizon and mitigated communication range. *For a surface ship, refractive effects are important only for energy at elevation angles within a few degrees relative to the local horizontal.* (This is known as the low-elevation problem.)

Refractivity is fundamentally characterized by the refractive index n. Because n is very close to unity (e.g., 1.00300), the refractivity N is defined by the expression

$$N = (n - 1) \times 10^6 . \tag{1}$$

Here, N assumes values (e.g., 300) that are easier to handle. A further mapping is frequently made relating N to the modified refractivity M, since height profiles of M allow easy recognition of ducting layers[1,2] (Fig. A). The expression for M is given by

$$M(h) = N(h) + 0.157h , \tag{2}$$

where h is the height above the surface in meters. The radar refractivity N has been determined empirically[1] by the expression

$$N = \frac{77.6P}{T} + 3.73 \times 10^5 \frac{e_w}{T^2} , \tag{3}$$

where P is the atmospheric pressure (mB), T is the air temperature (K), and e_w is the water vapor pressure (mB). Water vapor pressure depends only on relative humidity and temperature, varying from near 0 to approximately 30 mB in most environments.

M is defined so that energy bends parallel to the Earth's surface when the profile slope is exactly vertical (for example, at 300 m in Fig. A, panel 5). Therefore, a negative slope indicates that energy will be refracted toward the Earth and reflect from its surface (e.g., ducting). Other categories of refraction are superrefraction, standard propagation, and subrefraction; these are presented in Fig. A in terms of profiles of M. The presence of a negative slope, however, does not guarantee that radar energy will be trapped (ducted) by that region. The impact on radar propagation depends on the relative heights of the transmitter and receiver or target relative to the duct height, the extent and strength of the negative slope, and the radar frequency.[2] Furthermore, negative slopes in refractivity profiles need to persist over an appreciable range (e.g., at least 5 nmi or more) in order to significantly impact propagation. Figure B illustrates how the direction of a propagating ray is bent for several of the refractivity conditions defined next.

Standard atmospheric refraction (also called 4/3 Earth). The U.S. standard atmosphere refers to profiles of water vapor, pressure, and temperature that are averages of many radiosonde soundings taken throughout the world. The refractivity profile calculated from these average profiles is called the standard atmospheric refractive profile. Below 1500 m, this profile has a vertical slope of approximately 118 M units per km (see Fig. A, panel 1). The term "4/3 Earth" comes from a simple, convenient way that radar engineers account for refractive effects of the standard atmosphere in the radar range equation. For such an atmosphere, radar rays may be drawn as straight lines relative to a spherical Earth whose radius is 4/3 the actual Earth radius. In this new mapping, the same relationship between the range to the target and the height of the target is preserved. Hence, the terms "standard atmosphere" and "4/3 Earth atmosphere" are often used
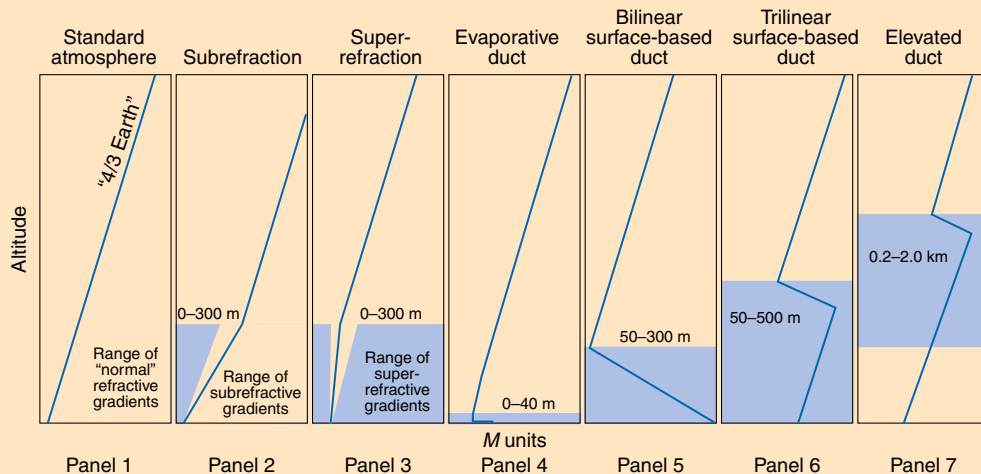
Figure A. Types of refractivity conditions.
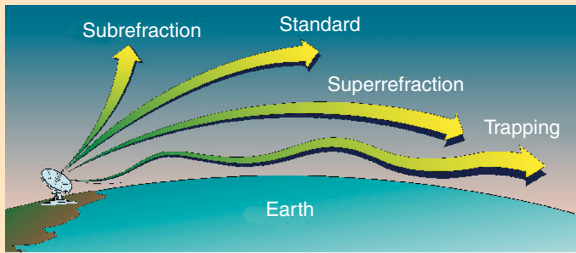
Figure B. Effect of refractive conditions on propagating ray.

interchangeably. Practically speaking, a standard atmospheric refractivity profile closely approximates the slope of a well-mixed atmosphere.

Subrefraction. Subrefraction results in a reduced radar horizon because radar energy is refracted away from the Earth's surface. Formally, subrefraction occurs when $dM/dh > 118\,M$ units per km near the surface but becomes significant when $dM/dh > 157\,M$ units per km (Fig. A, panel 2). Persistent, widespread areas of severe subrefraction can often be correlated on synoptic maps with warm air masses moving over cooler water.[3]

Superrefraction. Superrefraction results in enhanced propagation relative to standard atmosphere, but conventionally does not include the strong ducting effects of surface-based and evaporative ducts. Superrefraction occurs for refractivity profiles in which $0 < dM/dh < 118\,M$ units per km (Fig. A, panel 3). The radar effects resulting from superrefraction are often difficult to distinguish from those resulting from small to moderate evaporative ducts.

Evaporative ducting. Evaporative ducting is the most prevalent refractive effect for low-altitude radar performance over the sea. This phenomenon results from a rapid decrease in humidity just above the ocean due to evaporation. The resulting negative humidity slope causes a negative slope in modified refractivity and therefore a duct just above the surface. The change in the humidity slope has a characteristic curved (log-linear) shape seen in Fig. A, panel 4. The height of the duct ranges from 0 to 40 m and is typically smaller than 10 m along the Mid-Atlantic coast. Evaporative ducts always exist when the sea-surface temperature is warmer than the overlying air and can be estimated from simultaneous measurements of air temperature, sea temperature, humidity, and wind speed. The degree of ducting depends on duct height, radar height, elevation angle, and radar frequency. Higher frequencies (shorter wavelengths) are more likely to be ducted than lower frequencies.

Surface-based ducting. Surface-based ducting is caused by features of atmospheric circulation, for example when warm, dry continental air flows offshore. The temperature inversion aloft causes a stable condition that traps moisture below. In this case, large decreases in water vapor pressure and increases in temperature between the moist marine layer

and the dry air aloft cause rapid decreases in modified refractivity at the boundary. An example is the Santa Ana winds, which occur annually in Southern California. Surface-based ducts can also be caused by large-scale subsidence of cold, dry air,[4] such as occurs in the vicinity of mountains, within a high-pressure system, or as a result of nighttime cooling. Although surface-based ducting is generally less likely than evaporative ducting, there are some regions and seasons (e.g., the Arabian Gulf in the summer) where surface-based ducting is dominant.[5] These ducts cause radars to receive land and sea clutter from long ranges, resulting in difficult-to-predict performance degradations. A surface-based duct can be either "attached" to the surface, resulting in a bilinear duct shown in Fig. A, panel 5, or "detached" as in the trilinear duct of Fig. A, panel 6. When the surface-based duct height is low (<60 m), there is a substantial increase in radar energy on low-elevation targets as well as the sea surface. Surface ducts with high duct heights or a higher trilinear duct will cause so-called "clutter rings" and "skips zones" on a radar display due to ducted surface clutter.[6] Ducting depends on radar frequency or wavelength as[4,7]

$$\lambda_m = CD\Delta M^{1/2} \ , \tag{4}$$

where

λ_m = the maximum ducted wavelength (m),
C = 3.77×10^{-3} or 5.66×10^{-3} for a surface-based duct or elevated duct, respectively,
D = the duct height (m), and
ΔM = the difference between the minimum of M at the top of the duct and the maximum within the duct (this is not necessarily the value of M at the bottom of the duct).

Elevated ducts. Elevated ducts may be caused when elevated colder air flows over moist air, resulting in local compression and heating of the atmosphere at higher altitudes. This results in an elevated temperature inversion and trapping of the moisture at altitude (Fig. A, panel 7). Elevated ducts may also be caused by the same mechanisms that cause surface ducts, such as the flow of warmer, dry air over cooler, moist air. This again may result in an elevated temperature inversion with trapping of moisture, but the inversion is not strong enough to connect the duct with the surface. In contrast to surface-based ducts, which can significantly impact near-surface radars, elevated ducts have no appreciable impact on the performance of shipboard radars. On the other hand, airborne radars within the elevated duct may be affected.

The process of determining whether a particular refractivity condition helps or hurts radar performance is complicated. It depends on many factors including power on target, power on clutter sources, target cross section for a given aspect angle, clutter cross section, the time and frequency dependence of target and clutter returns, radar setup parameters and loading, etc.[8]

terrain height. Atmospheric refractivity is affected by wind speed, sea state, sea temperature, air temperature, and relative humidity. Sea state and refractivity also affect radar sea clutter; land characteristics affect land clutter. Atmospheric circulation produces large-scale

refractive structures such as land/sea breeze inversions and weather fronts. Ocean currents have a direct impact on sea temperature.

The Laboratory has developed a unique capability to characterize critical aspects of the ocean environment

that impact Navy shipboard combat systems through their effects on microwave and infrared propagation. In particular, APL produces environmental measurements and statistics, analysis techniques, instrumentation, models, simulations, and tactical decision aids (TDAs) to support surface ships' communications and defense against seaskimming missiles. This ability, in part, grew out of a need to understand the capabilities and limitations of the Terrier and Aegis combat systems in the 1980s. Success led to support of a wide variety of U.S. Navy and NATO programs for system analysis, at-sea testing, and sensor development.

One of the primary defensive concerns is seaskimming missiles. Environmental impacts on missile detection can be complex. The environment may limit radar detection ranges and cause degradations in track continuity through the effects of land, sea, and precipitation clutter. Communications systems may experience outages or periods of increased interference. Weapon systems may encounter midcourse guidance errors and variations in illuminator power-on-target and bistatic clutter into the missile, which affect the missile engagement envelope. In addition, the environment affects radar configuration, ship stationing, situational awareness, and missile doctrine selection.

This article describes the development of environmental characterization techniques for anti-air warfare performance assessment that started with support for SPY-1 radar analysis and at-sea testing. It provides a history of how the instrumentation expertise of APL's Space Department was combined with meteorological/oceanographic (METOC) experience from the Submarine Technology and Fleet Systems Departments to provide environmental characterizations as input to an emerging class of parabolic equation–based propagation programs. The resulting process was refined over the years through accumulated experience resulting from application to system simulation and analysis, at-sea field test support, statistical analysis of propagation link and environmental measurements, and, more recently, shipboard TDAs for the Fleet. Finally, this article suggests future applications associated with combat systems design, modeling and simulation, and advanced TDAs.

EVOLUTION OF APL ENVIRONMENTAL SUPPORT

Radar Simulation and Propagation Models

In the 1970s, the Navy faced the emerging threat of low-altitude, high-speed cruise missiles and the need for a combat system that would allow more reaction time against these incoming missiles. APL helped the Navy design an integrated combat system for surface ships with a multifunction phased array radar, SPY-1, as the primary sensor. SPY-1 operates in S band. The performance of

the system was assessed with a radar simulation, begun around 1979 and funded by the Aegis Shipbuilding Program Office (PMS-400). The need for high-fidelity simulation in addressing the low-elevation problem led to the initial APL SPY-1 FirmTrack simulation. FirmTrack was tested against field exercise data, and its performance varied considerably for similar ship-threat scenarios. It became clear that the ocean environment was an important factor in system performance.

A series of explorations, including Navy live-fire missile exercises, indicated that radar propagation had to be addressed in the radar simulations. This led APL to investigate environmental effects on radar propagation, concluding that a high-fidelity radar propagation model was needed to address environmental features at low elevation angles, largely because of strong refractivity gradients that can occur near the ocean surface.

In 1982, the Aegis Program Office began supporting APL development of advanced low-elevation propagation models. By 1985, the FirmTrack simulation could accept propagation loss information from a high-fidelity parabolic equation–based propagation program, Electromagnetic Parabolic Equation (EMPE), for hypothetical environments. EMPE, developed by APL's Submarine Technology Department,[9,10] was a big step forward in radar propagation modeling. The result was unprecedented realism and accuracy in propagation predictions, as well as an order of magnitude increase in computation speed. The former Fleet Systems Department adapted the EMPE code to anti-air warfare applications.[11] Advancements in capability led to the EMPE program code being renamed the Tropospheric Electromagnetic Parabolic Equation Routine (TEMPER).[12,13]

Figure 1 shows a sample radar propagation factor plot from TEMPER modeling a large surface-based duct for a radar frequency of 3 GHz. Propagation factor, or pattern propagation factor, is a ratio used to express radar propagation loss or gain relative to free space spreading[8]:
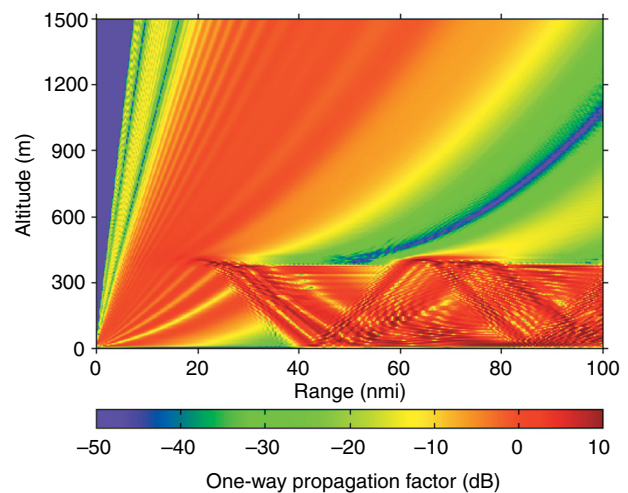

Figure 1. TEMPER prediction for a large surface-based duct.

$$PF(r,\theta) = \frac{E(r,\theta)}{E_0(r)},$$

where PF is a propagation factor depending on range r and elevation angle θ, E is the electric field strength in a realistic atmosphere at the given r and θ, and E_0 is the electric field strength that would exist at range r in free space in the antenna beam maximum. Note in Fig. 1 the lobing pattern in elevation angle due to the multipath interference of energy reflected off the ocean surface. Also note the trapping of radar energy in the surface duct whose height is 426 m. The trapping (or ducting) causes long-range propagation and clutter return along with a shadow zone above 426 m beyond a range of about 30 nmi.

The Laboratory has been developing radar simulations for many years. APL's FirmTrack—a high fidelity dwell-by-dwell Monte Carlo statistical model of key SPY-1 radar functions and algorithms for Aegis—is one of an inventory of simulations that has been used extensively since the late 1970s. It has supported scenario development, conduct, and evaluation for many Aegis at-sea exercises, and, since the late 1980s, many Aegis cruiser and destroyer field exercises, combat system evaluations, and SPY radar analyses with significant visibility in the Navy and DoD communities. A partial list of these analyses is provided in Table 1. FirmTrack is regularly updated as Aegis baselines and experimental loads evolve and is modified as necessary to accommodate system engineering trade studies and at-sea test events.

TEMPER and FirmTrack development continues today[14]; TEMPER is recognized as a benchmark against which other Navy programs are compared for accuracy. APL supports over 100 TEMPER users for a range of DoD sponsors (see the article by Newkirk et al., this issue). TEMPER and FirmTrack were both accredited by PMS-465 and PMS-400B for depth-of-fire simulations for Cooperative Engagement Capability (CEC) technical evaluation (TECHEVAL). Major TEMPER upgrades are sent to SPAWAR, San Diego, for incorporation into the Advanced Propagation Model, which is designated as the next standard radar propagation model for at-sea prediction.

Radar Clutter

Another impact of the environment on radar performance related to atmospheric refraction is surface clutter from sea and land. Ducting can significantly enhance clutter levels relative to those seen under standard atmospheric conditions. Reilly and Dockery[15] developed an approach that accounted for ducted sea clutter. In 1991, the ducted clutter model, named Refractivity with Propagation (REPROP), showed excellent agreement with measurements taken during field tests at Wallops Island, Virginia. The agreement provided confidence that the models could support analyses comparing existing and planned SPY-1 clutter processing. APL also participated in a study mandated by the U.S. Congress to evaluate radar performance (including SPY-1) in a clutter-limited environment and is actively developing the radar land clutter model.[16]

Table 1. System performance analyses.

Navy test support	Timeframe
Terrier AN/SPG-55B test	Oct 1984
Mk 92/Terrier Atlantic Fleet Weapon Test Facility exercises	Sep–Oct 1986
USN/FGN missile exercises	May 1987–present
New Threat Upgrade OPEVAL	Apr 1988
Tartar Developmental Test (DT)	Nov 1989
Terrier/Tartar Tomahawk exercises	Apr–Sep 1991
Terrier Desert Shield/Storm Upgrade OPEVAL	Sep 1990
Cooperative Engagement Capability (CEC) DTs	Aug 1990/Feb–Jun 1994/ Jul–Aug 1997/May–Jun 1998
Standard Missile-2 BLK II DT/Operational Test (OT)	Jul–Aug 1991
Mk 92 DT	Oct 1990–Jan 1991
DDG 51 Combat System Ship Qualification Trials (CSSQTs)/DT/OT	Oct 1991–Jan 1992
Ship Self-Defense System (SSDS)/Integrated Ship Defense System (ISDS) TECHEVAL/OPEVAL	Jun 1997
Airship Demo Program	Oct 1994–Jan 1996
CEC Baseline 2 DT/OT and work-up underways	Feb 1999–present
(Other U.S. and NATO systems)	

Profiles of Atmospheric Data

Radar propagation predictions with high-fidelity models such as EMPE or TEMPER require accurate environmental input data. The need for improved environmental information spurred development of new environmental sensors and instrumentation. The instrumentation expertise of APL's Space Department was enlisted to build sensors to provide environmental characterizations.

By 1986, APL had developed an instrumented helicopter system (Fig. 2) to collect range-dependent refractivity data in coastal (littoral) environments.[17,18] The helicopter typically flies a "sawtooth" pattern (Fig. 3), collecting accurate data during descents every 4 to 6 km. This profiling technique is necessary to capture the two-dimensional (e.g., height and range) variability that represents an input to the TEMPER code.[19,20] Classic work by Goldhirsh et al.[3] determined that long-range propagation can occur when offshore winds create large surface-based ducts off the coast of Wallops Island. The environmental helicopter tracks these large-scale features by carefully selecting the maximum altitude for each profile in the sawtooth pattern. The Large-Scale Atmospheric Refractivity Range Interpolator (LARRI) was developed to track large-scale refractivity structures with altitude in the helicopter data set, rather than interpolate or average profiles for input to the radar propagation codes.[11] LARRI was contributed to the Naval Environmental Prediction Research Facility in 1989.

Techniques for measuring and characterizing radar refractivity in the environment were eventually automated and used in a series of tests to validate the TEMPER program. The APL helicopter system was operated in support of Aegis Combat System Ship Qualification Trials (CSSQTs). Good agreement between actual and reconstructed SPY-1 performance led to the use of APL's helicopter system as a standard part of Aegis CSSQTs. The Laboratory contributed a set of helicopter instrumentation to the Point Mugu Naval Station for support of the CSSQTs.

By 1990, the use of instrumented helicopters became a regular part of APL field exercises and Navy tests. High-quality environmental assessment is possible when the environmental helicopter can land and refuel near the measurement location, with a nominal run time of 2 h. For some field exercises, this is not possible, and the Navy required a measurement technique that could be deployed from ships underway.

From the late 1980s through the 1990s an APL team experimented with a variety of unique inventions for making atmospheric profiles. The "yo-yo sounder" was a small helicopter, powered by a radio-controlled model airplane engine, that carried environmental sensors from the surface to about 300 m (Fig. 4). The "balloon yo-yo" was a meteorological balloon and standard radiosonde package, ballasted to near weightlessness (Fig. 5). A model airplane engine hung from the radiosonde and provided intermittent upward thrust for a pre-timed interval. A switch attached to a trailing wire sensed the surface and restarted the engine to accomplish the yo-yo profiling. The Laboratory also developed rocketsondes, which are miniature radiosonde packages launched on a model rocket. At a predesignated altitude, 300 to 600 m, a parachute is ejected and the package
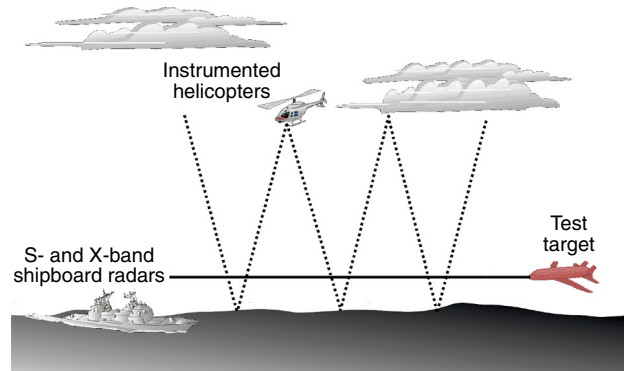

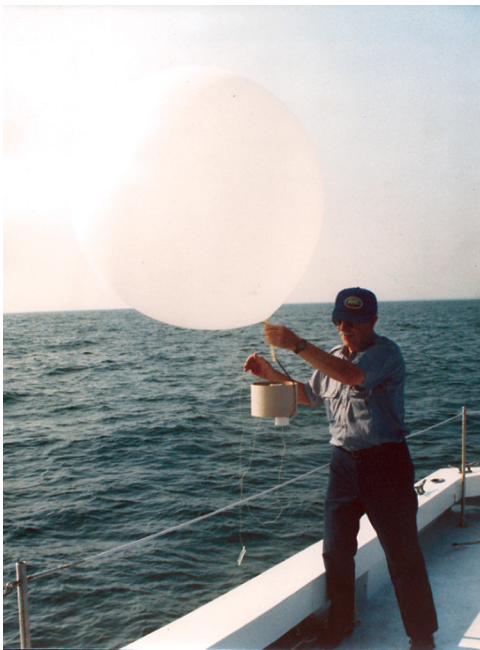**Figure 3.** Helicopter sawtooth pattern. Temperature, pressure, humidity, altitude, latitude, longitude, and meteorological measurements are collected on helicopter descents.

Figure 2. APL helicopter instrumentation.

Figure 4. Yo-yo helicopter.

Figure 5. Balloon yo-yo.

Figure 6. John Rowland of the APL Air Defense Systems Department led a team that experimented with a variety of unique inventions. He is shown here with an early rocketsonde prepared for launch.
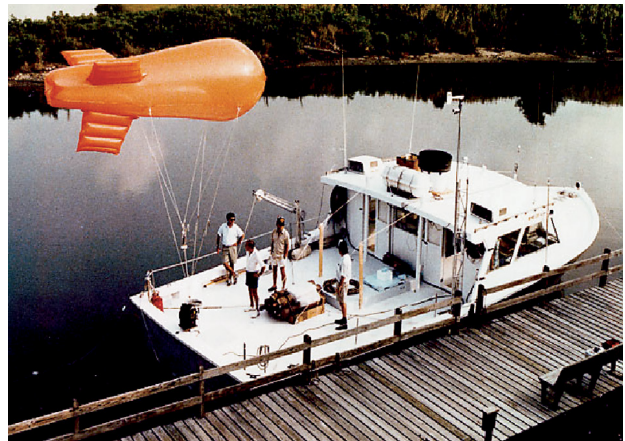

Figure 7. R/V *Chessie* with kytoon.

descends to Earth while telemetering the pressure, temperature, and humidity to a receiver onboard a ship or other surface location (Fig. 6). The rocketsonde vertical data resolution is about 3 m.

A profiling instrument package was also deployed on a small dirigible, now dubbed a "kytoon" (Fig. 7), which was cycled from a research vessel to about 300 m to measure surface ducts. Kytoon instruments included a sensor to measure the temperature turbulence spectrum. During this same period, Aegis was interested in an inexpensive expendable target for the Close-In Weapon System (CIWS) anti-aircraft guns. An "out/back rocket" (Fig. 8) was designed to fly about 4 nmi from the ship and return on a direct radial. A tunable coiled spring provided an enhanced radar cross section for the target.

Of all the measurement techniques attempted, the environmental helicopter is the platform of choice. When this is not feasible, rocketsondes or balloonsondes

Figure 8. The out/back rocket.

Figure 9. Balloon dropsonde.

are the preferred sensor packages. The rocketsonde has proven to be the most effective of the expendable sensor packages for providing real-time environmental information. It is a standard part of APL field exercises and an integral part of the Shipboard Environmental Assessment/Weapon System Performance (SEAWASP). The rocketsonde is useful for situations in which range independence is acceptable, for example, when ranges are relatively short or the atmosphere is homogeneous in range. When the shipping or storage of rocket motors is not acceptable for a test, balloon dropsondes are deployed (Fig. 9). These ascend on standard weather balloons, are released by a timer or fuse, and descend on parachutes like the rocketsondes, collecting equivalent data.

Long-Term Fade-Margin Link Measurements

Since 1985, APL has undertaken long-term measurement programs involving line-of-sight (LOS) and over-the-horizon propagation links to assess in a statistical sense the propagation environment off the Mid-Atlantic Coast.[3,6,20–23] For example, 3 years of nearly continuous measurements of two LOS propagation links 39 and 44 km between Parramore Island and Assateague Beach (near Wallops Island; see Fig. 10) revealed that sustained deep fades dominated the statistics approximately 10% of the time. These deep fades were sustained for 2- to 48-h periods, were dominant during the winter, and were caused by extreme subrefraction ($dN/dh > 0$) arising from subtropical warm, moist air flowing over cooler water. These effects were determined to be sustained over extended periods of time since they were generally associated with Atlantic high-pressure systems (e.g., Bermuda highs), which may last for several days.[3,23]

A year of continuous measurements was also executed for an over-the-horizon propagation link extending between Dam Neck and Wallops Island, a distance of about 128 km. These statistics demonstrated that
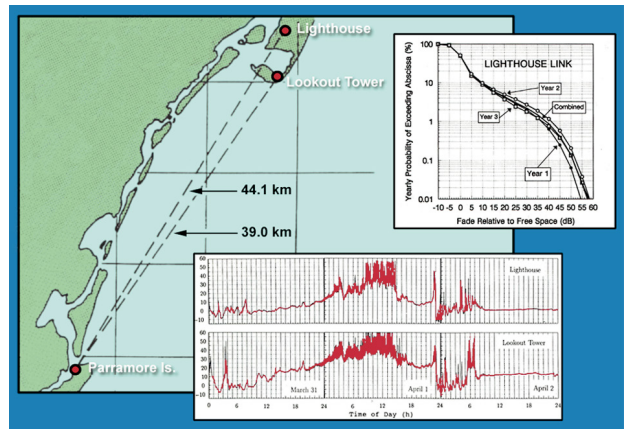
Figure 10. Fade-margin links.

evaporation and surface-based ducts dominated the statistics, with the spring–summertime period exhibiting more ducting phenomena (e.g., 50% of the time) compared to the fall–winter period (20% of the time).[21]

Real-Time Propagation Assessment

Through telephone call-up procedures, APL has developed a methodology in which signal levels may be monitored in real time from three propagation links in the vicinity of Wallops Island. Two of these links

are LOS (Cedar Island/Assateague State Park) and the other is the over-the-horizon link described previously. By matching real-time signal levels with those obtained from evaporation duct models, equivalent duct heights may be ascertained in real time. These results are simultaneously compared with real-time measurements made using the APL environmental measurements boat, R/V *Chessie* (Fig. 7), for consistency. This real-time capability has proven highly useful to better assess propagation conditions for a multitude of tests performed near Wallops Island.

Radar Ducting and Instrumentation

During the 1980s, a controversy existed concerning the relative importance of surface ducts and evaporative ducts for explaining observed radar propagation. From results of Navy tests off Wallops Island, where significant surface ducting is observed, the presence of surface-based ducts was believed to be the overriding issue. An initial TDA called the System Performance and Response (SPAR), with rocketsondes and analysis algorithms, was tested on USS *Leyte Gulf* (CG 55) in this same period. The evaporative duct was a theoretical consideration,[24] not believed to have much effect on radars operating at heights above it. However, the fade-margin links and field tests made during evaporative ducting conditions helped determine that the surface properties, including evaporative ducts, could be important. As a result, APL outfitted *Chessie* circa 1990 with instruments to measure surface properties that affect evaporative ducts, e.g., sea temperature, air temperature, relative humidity, wind speed, atmospheric pressure, and sea state.[25]

The APL team fielded a variety of sensors during the initial development period, 1990 to 1995. Fixed sensors were mounted on masts at 6 and 10 m. The team attempted many schemes to measure ocean surface properties and discovered how difficult it was to get good baseline measurements of air–sea surface properties from a rocking ship. Rocking while adrift made a boom infeasible, so a series of detached floats was developed. The first was the Styrofoam sled. Success led to advanced versions, including a 2-m catamaran, 1-m catamaran, 1-m profiler, 0.3-m profiler, and 4-m catamaran. An 8-m version is currently under construction. The 1-m (Fig. 11) variant houses fixed air temperature and relative humidity sensors at 1-m and about 2-cm heights, respectively, and a sea temperature sensor at about 2 cm below the water surface. Observations of temperature, humidity, and refractivity defied air–sea and evaporative duct models. This led to the development of the profilers designed to yield yo-yo profiles of environmental parameters (Fig. 12).

Since it is not feasible to deploy catamarans from moving ships, expendable sensor floats dubbed "float-sondes" (Fig. 13) were developed to measure surface
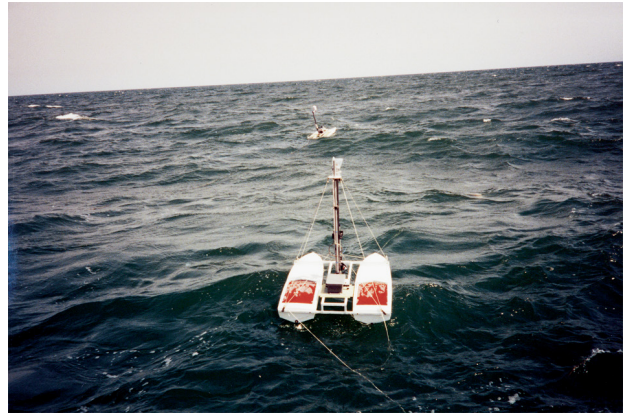

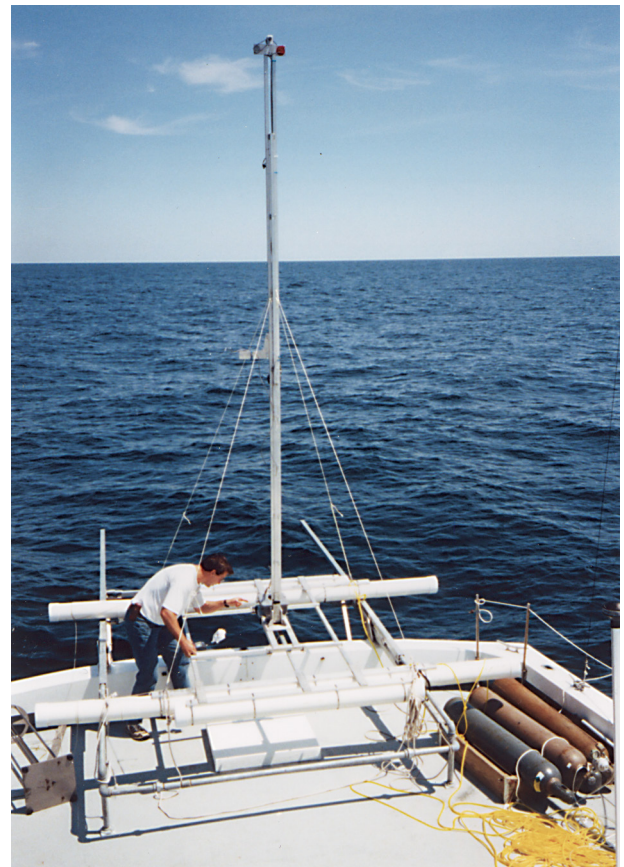**Figure 11.** The 1-m catamaran.

Figure 12. The 4-m profiler.

properties. These floats measure sea temperature, air temperature, and relative humidity at the surface. The current inventory of Air Defense Systems Department field test equipment for environmental assessment is presented in Table 2.

Evaporative duct models were implemented on the *Chessie* data collection system to provide real-time display of evaporative duct height. The models used concepts developed at the Naval Research Laboratory, San Diego, by Jeske[24] and Paulus.[25] A long series of
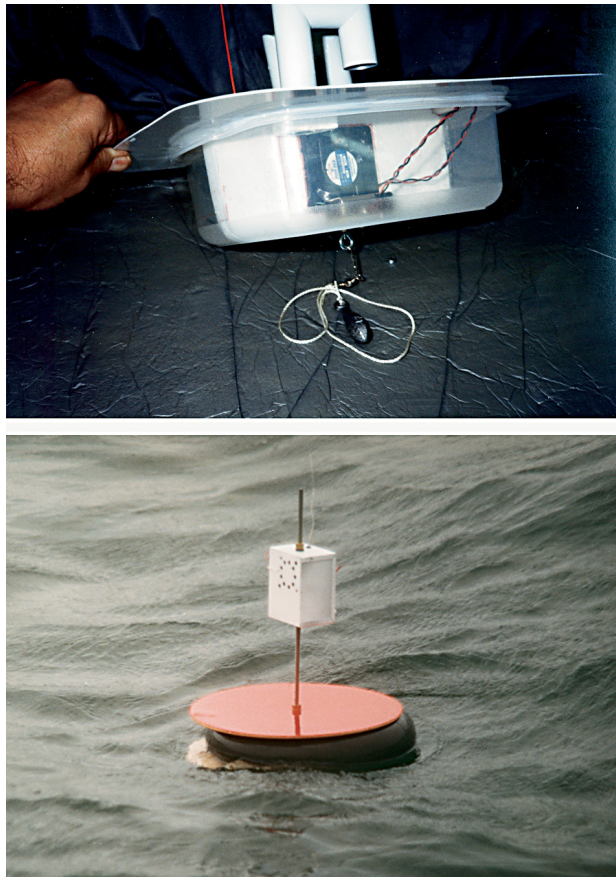
Figure 13. Floatsondes.

sea tests led to the development of the Constant Virtual Temperature (CVT) model, also known as the Rowland-Rottier model, which has proven to be reliable in the field. The CVT model is currently incorporated into SEAWASP and the SPY Sliderule program developed by the Naval Surface Weapon Center, Dahlgren Division. This is a modification of the Paulus-Jeske model that assumes constant virtual temperature T_V

of the air between the ocean surface and the sensor mast height. The CVT also predicts the surface relative humidity from the relative humidity measurement at the mast height and an empirical predictor based on regression analysis of at-sea observations. The CVT surface humidity is generally predicted to be above 90% but rarely 100%, whereas the Paulus-Jeske model assumes saturation (RH = 100%) at the surface.

Improvements in the ability to predict the evaporative ducts paralleled the development of oceanographic and meteorological sensors. Model testing and TDA development are integral to *Chessie* field tests. Research into evaporative duct models continues at APL.[26] The next-generation evaporative duct model is being developed in conjunction with the Naval Postgraduate School based on the work of Liu et al.[27] and Fairall et al.[28]

The combined set of surface data and atmospheric profiles (from rocketsondes, balloonsondes, or helicopter profiles) is merged into profiles by software developed at APL. The Rocketsonde Evaporative Duct (RED) program currently edits refractivity profiles, merges combined profiles, smoothes (decimates) resultant profiles, and modifies the near-surface profile to account for convection when it is present. This is necessary because convection produces turbulent mixing from the ocean surface up to the convective height (cumulus cloud height when clouds are present).

Throughout the early development period, numerous field tests and Navy Fleet exercises for a variety of sponsors gave APL opportunities to empirically evaluate accepted meteorological modeling assumptions and refine environmental characterization procedures. The insights into combat system performance that were provided by incorporation of METOC data into postexercise analysis led to renewed calls for an operational capability to leverage off the SPAR TDA. Several sensitivity studies, as well as field test and Fleet

Table 2. Current APL inventory of field test equipment.

Platform	Sensors
Helicopter	$T_{sea,IR}$ and H_{radar}; T_{air}, RH, P, U_{wind}, and θ_{wind} versus height
Chessie, SEAWASP	T_{air}, RH, $T_{sea,IR}$, P, U_{wind}, and θ_{wind} at mast height
Rocketsonde (balloonsonde)	T_{air}, RH, and P versus height
Chessie kytoon	T_{air} and RH at 30 m
1-m catamaran	T_{sea}; T_{air} and RH at 0.02 and 1.0 m
1-m profiler	T_{air} and RH versus height from 0.1 to 0.9 m
4-m profiler	T_{air} and RH versus height from 0.1 to 3.5 m
Floatsonde	T_{sea}, T_{air}, and RH at surface

Note: T_{air} = air temperature, T_{sea} = sea temperature, $T_{sea,IR}$ = infrared sea temperature, H_{radar} = radar altitude, RH = relative humidity, P = atmospheric pressure, U_{wind} = wind speed, and θ_{wind} = wind direction.

exercise experience, provided the basis for APL's recommendations addressing near- and far-term METOC requirements for Aegis in 1994. These requirements were endorsed by Aegis and presented to the Navy METOC community in two symposia. Later, the near-term requirements were incorporated into plans for Moriah, which includes the replacement for the Navy Shipboard Meteorological and Oceanographic Observation System (SMOOS), and hence is known as SMOOS(R).

Tactical Decision Aids

Soon after the Aegis METOC requirements were established, the Navy Surface Warfare Development Group (SWDG) approached APL to develop a relatively simple and limited capability to help Aegis operators address the radar performance assessment problem during evaporative ducting conditions. The Laboratory devised procedures, selected the handheld instrumentation shown in Fig. 14, provided the CVT evaporation duct model, and used the FirmTrack simulation to generate a lookup table for the Sliderule program. APL is also developing automated TDAs for Aegis ships. Two present TDAs, SEAWASP and SMOOS(R), are described by Sylvester et al., this issue.

Figure 14. Handheld instruments.

SEAWASP Expert System

Extensive APL field experience produced a level of expertise that could be codified. It was observed that APL engineers could estimate evaporative duct heights, surface humidities, and other atmospheric phenomena from visual observations. It was thus realized that cues existed in the observable atmosphere for tactically important parameters. An attempt has been made to incorporate this expertise into the SEAWASP Environmental Expert System, a version of which will be incorporated into SMOOS(R).[29,30]

The SEAWASP Expert System uses continuous environmental data and expert rules to qualitatively determine radar refractivity conditions, evaluate significant changes in radar propagation conditions, and monitor the need to launch a rocketsonde. The inclusion of the rocketsonde is an option for Moriah/SMOOS(R). The rocketsonde provides quantitative assessments of conditions evaluated qualitatively by the Expert System logic and is essential for supporting radar performance assessments under many conditions. This complementary relationship between the SEAWASP Expert System logic and rocketsonde use is key to deploying the expendable sensors only when needed. Expert System logic thus reduces cost of use while maintaining continuous situational awareness of environmental changes. Care has been taken to make the SEAWASP expert rules consistent with the Aegis Core Tactics Tactical Memorandum (TACMEMO).

OTHER APL SUPPORT AREAS

Operational and Test Support

A critical ingredient in APL's success is the participation of field engineers in Navy at-sea trials. This is the only way to be certain that the Laboratory is bridging the gap between its engineers and the warfighters. In the past, APL has

- Supported the Mountain Top series of tests that addressed the feasibility of the CEC
- Demonstrated that EM propagation ranges depend on environmental conditions
- Enabled USS *Anzio* (CG 68) and USS *Cape St. George* (CG 71) to collect CEC support data from APL mast sensors during the CEC TECHEVAL

The Laboratory continues to support several ongoing Navy projects, e.g.,

- Development of SEAWASP with shipriders during sea trials; in-port repairs; and enhancements in reaction to feedback from operators
- At-sea support of TDA development
- Regular participation in Navy qualifications tests such as the CSSQTs and TECHEVALs of new systems

• Updates to the TACMEMO and evaluation of the radar assessment procedures during *Chessie* and Aegis field tests

In 2001, a Navy white paper called for better use of environmental information and better communication between Navy METOC observers and radar operators. A Navy METOC conference was convened to discuss these requirements. One result was the request by SWDG for an environmental "rules of thumb" document. This document was developed by APL in collaboration with the Naval Postgraduate School and provides straightforward guidance for the exploitation of ocean environmental information, with a focus on environmental conditions that impact radar performance. Figure 15 is an excerpt from that document. It shows how the environment is assessed for the probability of a radar surface-based duct. This assessment is based on the relative heights of the calculated cloud base (CCB) via an infrared temperature measurement and the height of the lifting condensation level (LCL). The LCL is determined by the lapse of the temperature–dew point spread measured at the ship reference level. The rules are derived directly from the SEAWASP Environmental Expert System.

Design Support

In addition to the design of environmental sensors and the SEAWASP TDA, knowledge of the environment has allowed APL to contribute to the design of Navy systems and sensors to optimize them for the real world. These include the SPY series of phased arrays to compensate for specific environmental effects, Aegis combat systems, radar processing algorithms for sea and land clutter, and the rocketsonde system. The fade-margin link study contributed to the design of CEC communications to contend with radio propagation effects. APL's environmental analysis efforts have had a fundamental impact on Navy new-generation radars. One goal of the radar design work is to minimize the sensitivity of combat system performance to environmental effects.

ON THE HORIZON

The Navy Surface Fleet has requirements for the future that include improved environmental sensors, an understanding of radar performance in the littoral, the need for area-wide environmental data, three-dimensional environmental representations, and data fusion. Several major APL successes have
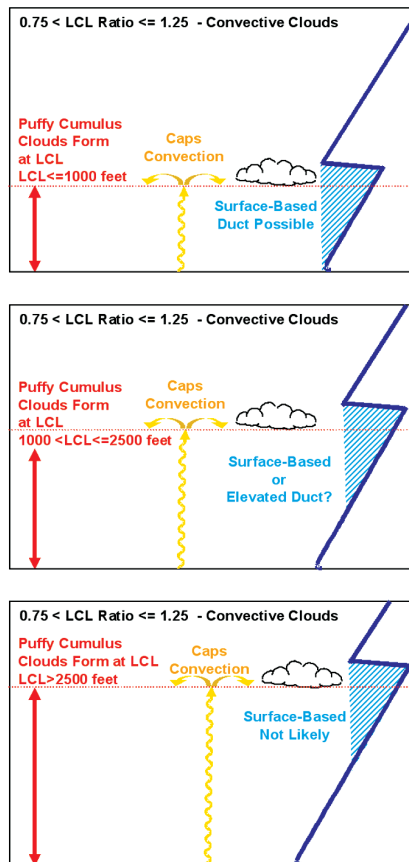
Clouds are near LCL. Verify that they appear to be fair-weather cumulus. If so, a duct should be close to the LCL. It is likely to be a surface-based duct since it is below 1000 ft.

Clouds are near LCL. Verify that they appear to be fair-weather cumulus. If so, a duct should be close to the LCL. It is possibly a surface-based duct since it is below 2500 ft.

Clouds are near LCL. Verify that they appear to be fair-weather cumulus. If so, a duct should be close to the LCL. It is probably an elevated duct since it is above 2500 ft.

Figure 15. "Rules of thumb" example. The LCL ratio = LCL/CCB (via infrared temperature measurement). An LCL ratio ≅ 1 indicates that the cloud base temperature is consistent with clouds forming at the LCL as expected for a convective surface layer (unstable atmosphere).

established trends that position us to address some of these issues.

Advanced Sensors

The current suite of APL helicopter sensors has produced outstanding results. Refinements of helicopter sensors continue today. APL may support future upgrades to the environmental helicopter at Point Mugu. Helicopter deployments of APL dropsondes in the Arabian Gulf demonstrated that an operational helicopter could contribute to environmental characterization during its mission. The future may see environmental sensors on operational helicopters.

APL continues to support improvement to the SPY-1 series of phased array radars, including refinements to take advantage of the Laboratory's understanding of environmental effects. Work is under way to develop phased array radars that operate at a higher frequency than SPY-1. The higher frequency increases resolution compared to S-band, but is more sensitive to environmental effects. For example, evaporative ducts have a greater effect at higher frequency (shorter wavelength), and this increases the importance of evaporative duct models. It also places more emphasis on the catamaran profilers for describing the physics of air–sea interaction and the evolution of near-surface refractive features. The environmental assessment work centered around S band may not be adequate for higher-frequency radar propagation.

APL engineers are considering a practical handheld ceilometer, which would allow implementation of the SEAWASP Environmental Expert System on all ships using the current suite of TACMEMO handheld sensors and software. The SEAWASP Expert System is also expected to undergo refinements as the validation effort continues.

SMOOS(R) Enhancements

The Navy plans to eventually deploy SMOOS(R) on its ships. We anticipate that enhancements will be required as the Navy receives feedback from a large number of systems. SMOOS(R) is designed with an open architecture, capable of accommodating a variety of additional sensors. APL is currently investigating the use of a near-infrared ceilometer for measuring cloud layer heights, a visibility/precipitation sensor to measure scattering properties of local atmosphere, and improved infrared thermometers for sea surface temperature. Other remote sensors will be investigated to explore the possibility of obtaining a three-dimensional characterization of refractivity for the battle group.

Data Assimilation and Fusion

There exists a need to assimilate meteorological data from dissimilar sources into a common form and fuse them with other sources of information, including satellite data and model predictions by the Navy's Fleet Numerical Meteorological and Oceanographic Center. The goal is a unified three-dimensional picture of refractivity. The Navy research community, including APL, recognizes the need to explore sensors and regional meteorological models to address this issue. With SMOOS(R) on all ships in a battle group, the first step can be taken to share the environmental data to give the battle group an area-wide picture of the near-surface atmosphere.

Model Issues

Development of models for environmental assessment is ongoing at the Laboratory. Areas for progress involve a better understanding of radar propagation through and above foliage and ground cover and applications for three-dimensional characterization. An effort is under way to improve the modeling of the forward reflection spectrum from a rough sea surface to improve boundary conditions for radar propagation modeling at very low elevation angles. The various clutter models are being integrated into an Integrated Clutter Model for the generation of site-specific scenarios that address clutter from land, sea, rain, dust, and sand. In addition, the controversy over boundary conditions for evaporative duct models will become more important for future higher-frequency radars. Experimental meteorology may improve atmospheric modeling and lead to better formulations for evaporative duct height characterizations.

CONCLUSION

The ocean environment has not fundamentally changed since 1814, when USS *Constitution* escaped the British fleet. Tides still occur twice each day, and the wind still drives the waves and general circulation of the ocean. It still takes dedication and courage to fight at sea. However, our technology has changed. Instead of optical detection scenarios that resolve in hours, we now depend on radar detections with reaction times as short as a few seconds. In the last decade the focus of U.S. military strategy turned to regional conflict. That puts the Navy in the coastal ocean, where the environment plays a bigger role than in blue ocean scenarios. APL has a successful history of investigation into ocean environmental effects on Navy surface ship combat systems. We will continue to support Navy programs that require an understanding of the ocean environment.

REFERENCES

[1]Bean, B. R., and Dutton, E. J., *Radio Meteorology*, Dover, New York (1968).
[2]Kerr, D. E., *Propagation of Short Radio Waves*, McGraw-Hill (1951).

[3]Goldhirsh, J., Dockery, G. D., and Meyer, J., "Three Years of C Band Signal Measurements for Overwater Line-of-Sight Links in the Mid-Atlantic Coast: Part 2. Meteorological Aspects of Sustained Deep Fades," *Radio Sci.* **29**(6), 1433–1447 (Nov–Dec 1994).

[4]Brooks, I. M., Goroch, A. K., and Rogers, D. P., "Observations of Strong Surface Radar Ducts Over the Persian Gulf," *J. App. Meteorol.* **38**(9), 1293–1310 (1999).

[5]Goldhirsh, J., "Influence of Coupled Environmental Features on Propagation Characteristics for an RF and IR Multisensor Radar System," *Radio Sci.* **32**(4), 1445–1453 (Jul–Aug 1997).

[6]Goldhirsh, J., and Dockery, G. D., "Propagation Measurements and Modeling at C Band for Over-the-Water, Line-of-Sight Propagation Links in the Mid-Atlantic Coast," *Radio Sci.* **26**(3), 671–690 (May–Jun 1991).

[7]Turton, J. D., Bennetts, D. A., and Farmer, S. F. G., "An Introduction to Radio Ducting," *Meteor. Mag.* **117**, 245–254 (1988).

[8]Skolnik, M. I., *Radar Handbook*, 2nd Ed., McGraw-Hill (1990).

[9]Schemm, C. E., Manzi, L. P., and Ko, H. W., "A Predictive System for Estimating the Effects of Range- and Time-Dependent Anomalous Refraction on Electromagnetic Wave Propagation," *Johns Hopkins APL Tech. Dig.* **8**(4), 394–403 (1987).

[10]Ko, H. W., Burkom, H. S., Skura, J. P., and Roberts, D. A., "An Analysis of EMPE Code Performance in a Selection of Laterally Inhomogeneous Atmospheric-Duct Environments," *Johns Hopkins APL Tech. Dig.* **9**(2), 89–100 (1988).

[11]Dockery, G. D., and Konstanzer, G. C., "Recent Advances in Prediction of Tropospheric Propagation Using the Parabolic Equation," *Johns Hopkins APL Tech. Dig.* **8**(4), 404–412 (1987).

[12]Dockery, G. D., "Modeling Electromagnetic Wave Propagation in the Troposphere Using the Parabolic Equation," *IEEE Trans. Antennas Propagat.* **36**(10), 1464–1470 (1988).

[13]Kuttler, J. R., and Dockery, G. D., "Theoretical Description of the Parabolic Approximation/Fourier Split-Step Method of Representing Electromagnetic Propagation in the Troposphere," *Radio Sci.* **26**(2), 381–393 (1991).

[14]Dockery, G. D., "Development and Use of Electromagnetic Parabolic Equation Propagation Models for U.S. Navy Applications," *Johns Hopkins APL Tech. Dig.* **19**(3), 283–292 (1998).

[15]Reilly, J. P., and Dockery, G. D., "Influence of Evaporative Ducts on Radar Sea Return," *Proc. IEEE Pt. F* **137**(2), 80–88 (1990).

[16]Reilly, J. P., and Lin, C. C., *Radar Terrain Effects Modeling for Shipboard Radar Applications*, FS-95-060, JHU/APL, Laurel, MD (Apr 1995).

[17]Rowland, J. R., and Babin, S. M., "Fine-Scale Measurements of Microwave Refractivity Profiles with Helicopter and Low-Cost Rocket Probes," *Johns Hopkins APL Tech. Dig.* **8**(4), 413–417 (1987).

[18]Babin, S. M., and Rowland, J. R., "Observation of a Strong Surface Radar Duct Using Helicopter-Acquired Fine-Scale Radio Refractivity Measurements," *Geophys. Res. Lett.* **19**(9), 917–920 (1992).

[19]Goldhirsh, J., and Dockery, G. D., "Propagation Factor Errors Due to the Assumption of Lateral Homogeneity," *Radio Sci.* **33**(2), 239–249 (Mar–Apr 1998).

[20]Goldhirsh, J., and Dockery, G. D., "Lateral Resolution Considerations of Refractivity Profiles Associated with Remote Sensing of Over-Water Coastal Regions," in *AGARD Conf. Proc.* **582**, *Remote Sensing: A Valuable Source of Information*, Toulouse, France, pp. II-1–II-12 (Oct 1996).

[21]Goldhirsh, J., Dockery, G. D., and Musiani, B. H., "Three Years of C Band Signal Measurements for Overwater Line-of-Sight Links in the Mid-Atlantic Coast: Part 1: Fade Statistics," *Radio Sci.* **29**(6), 1421–1431 (Nov–Dec 1994).

[22]Goldhirsh, J., and Musiani, B. H., "Signal Level Statistics and Case Studies for an Over-the-Horizon Mid-Atlantic Coastal Link Operating at C-Band," *Radio Sci.* **34**(2), 355–370 (Mar–Apr 1999).

[23]Goldhirsh, J., and Dockery, G. D., "K-Factor Statistics for Subrefraction in the Mid-Atlantic Coast of the United States," *Radio Sci.* **36**(6) (Nov–Dec 2001).

[24]Jeske, H., "State and Limits of Prediction Methods of Radar Wave Propagation Conditions Over Sea," in *Modern Topics in Microwave Propagation and Air-Sea Interaction*, A. Zancla (ed.), Reidel Pub. (1973).

[25]Paulus, R. A., *Specification for Environmental Measurements to Assess Radar Sensors*, Tech. Doc. 1685, Naval Ocean Systems Center (Nov 1989).

[26]Babin, S. M., Young, G. S., and Carton, J. A., "A New Model of the Oceanic Evaporative Duct," *J. Appl. Meteor.* **36**(3), 193–204 (1997).

[27]Liu, W. T., Katsaros, K. B., and Businger, J. A., "Bulk Parameterization of Air-Sea Exchanges of Heat and Water Vapor Including the Molecular Constraints at the Interface," *J. Atmos. Sci.* **36**, 1722–1735 (1979).

[28]Fairall, C. W., Bailey, E. F., Rodgers, D. P., Edson, J. B., and Young, G. S., "Bulk Parameterization of Air-Sea Fluxes for Tropical Ocean-Global Atmosphere Coupled-Ocean Atmosphere Response Experiment," *J. Geophys. Res.* **101**(C2), 3747–3764 (1996).

[29]*SEAWASP User Guide, Version 2*, ADS-01-013, JHU/APL, Laurel, MD (May 2001).

[30]Rottier, J. R., Rowland, J. R., Konstanzer, G. C., and Neves, M. R., *SEAWASP Expert System for Environmental Assessment*, ADS-01-032, JHU/APL, Laurel, MD (Oct 2001).

THE AUTHORS

J. ROSS ROTTIER is Senior Field Test Engineer in ADSD's Theater Systems Development Group. He received a B.S. in mathematics (Phi Beta Kappa) from Virginia Tech in 1977 and an M.S. in applied mathematics from The Johns Hopkins University in 1988. He worked for Columbia University from 1977 to 1980 as a marine geophysics research assistant and for the Coastal Engineering Research Center from 1980 to 1983 as a coastal oceanographer. Mr. Rottier joined APL's Submarine Technology Department in 1983, working on environmental effects on underwater acoustics, submarine tactical oceanography, radar TDA development, and laboratory research on internal waves. His current work includes air–sea interaction, environmental effects on radar propagation, and field testing of sensor systems. Mr. Rottier is a member of the Oceanography Society, the American Geophysical Union, and the American Meteorological Society. His e-mail address is ross.rottier@jhuapl.edu.
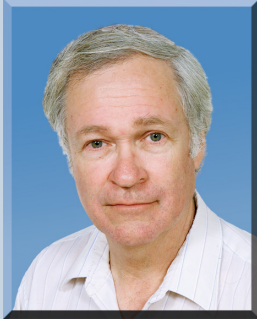
JOHN R. ROWLAND received a B.S.E.E. in 1968 from Kansas State University. After joining APL in 1968, he studied clear-air turbulence and precipitation using radar and other remote and *in situ* sensors. Since then, Mr. Rowland has developed automated techniques for analyzing ocean wave spectra and raindrop-sized spectra and has conducted studies related to the remote detection and identification of insects using radar and lidar. His current responsibilities include the study of meteorological effects on radar ducting and the development of meteorological sensors and systems for shipboard use. His e-mail address is john.rowland@jhuapl.edu.

GERALD C. KONSTANZER received an M.S. in electrical engineering from Drexel University in 1985. He joined APL in ADSD's Radar Systems Development Group, working primarily on analyzing impacts of the environment on ship-based combat system performance. This work involved atmospheric refractivity characterization, monostatic and bistatic clutter modeling, radar data analysis, and contributions to the TEMPER propagation program. In 1991, Mr. Konstanzer became a member of the APL Senior Professional Staff and a year later took on the role of SEAWASP Lead Engineer. He became Assistant Supervisor of the Propagation Analysis Section in 1994, and since 1996 he has been Supervisor of the System Analysis Section of the Theater System Development Group. His e-mail address is gerry.konstanzer@jhuapl.edu.
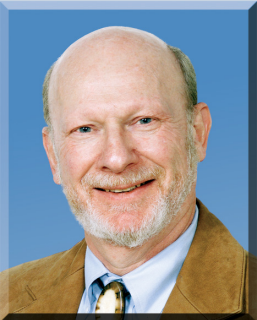
JULIUS GOLDHIRSH is a member of the APL Principal Professional Staff and Staff Scientist in ADSD's Theater Systems Development Group. He received a B.S.E.E. from Drexel University in 1958, an M.S.E.E. from Rutgers University in 1960, and a Ph.D. from the University of Pennsylvania in 1964. Dr. Goldhirsh joined APL in 1972 and for 14 years was Supervisor of the Space Geophysics Group in the Space Department. He is active in research dealing with propagation effects due to rain and terrain, and propagation in the presence of refractive environments for over-water and over-terrain point-to-point scenarios. Dr. Goldhirsh is a life fellow of the IEEE, and from 1994 to 1996 he was chairman of Commission F of URSI. His e-mail address is julius.goldhirsh@jhuapl.edu.

G. DANIEL DOCKERY received a B.S. in physics in 1979 and an M.S. in electrical engineering in 1983, both from Virginia Polytechnic Institute and State University. He also took graduate courses in physics and engineering at the University of Maryland. Mr. Dockery joined APL in 1983 and has worked in phased array antenna design, analysis and modeling of electromagnetic propagation in the troposphere, and the associated performance impacts on Navy radar and communication systems. He is a co-developer of advanced parabolic wave equation propagation models and has performed research in scattering, radar clutter, and atmospheric refractivity effects, including extensive field test experience. Navy programs supported by Mr. Dockery include Aegis, CEC, multifunction radar, and Navy Area and Navy Theater Wide TBMD. Mr. Dockery is a member of the APL Principal Professional Staff and Supervisor of ADSD's Theater Systems Development Group. His e-mail address is dan.dockery@jhuapl.edu.