Advances in Calculating Electromagnetic Field Propagation Near the Earth's Surface

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Τhe propagation of electromagnetic fields through the lower atmosphere is greatly affected by the environment, surface characteristics, and sensor configuration. This is particularly true for shipboard sensors that are tasked with defending themselves and nearby ships against low-altitude threats. With the Navy's focus now directed at coastal areas, the propagation environments include terrain backgrounds and complications caused by land–sea interactions. These littoral situations present not only a complicated field propagation problem for these sensors but also increased surface, volume, and discrete clutter sources that increase radar system loading and degrade communications capabilities. We summarize the recent advances in propagation modeling aimed at improving the ability to model propagation and clutter effects in littoral regions. While the improvements discussed here are particular to the Tropospheric Electromagnetic Parabolic Equation Routine (TEMPER), a propagation model developed at APL, they have also advanced the state of the art in propagation modeling. We also discuss the future directions of propagation modeling, outlining several areas of current research within APL that aim to further improve this critical capability.

INTRODUCTION AND MOTIVATION

The U.S. Navy has been aware of atmospheric impacts on radar performance since the first introduction of radar into the Fleet 50 years ago, and impacts on radio transmissions were observed much earlier. Attempts to understand and characterize these impacts also date back to the 1940s.[1] The review article by Hitney et al.[2] provides an introduction to some of the relevant propagation effects and references for early work in this field. The current "generation" of APL's work in understanding environmental impacts on systems began in conjunction with the development of the AN/SPY-1 radar for the Aegis weapon system around 1980.

The performance of systems radiating energy in near-horizontal directions is significantly affected by several environmental phenomena, including atmospheric refraction, diffraction over the spherical Earth (over sea) and around terrain features, scattering from sea and land, and attenuation by gaseous absorption and scattering from precipitation. Narrowing the discussion to radar detection of low-flying targets for the moment, refraction can cause detection ranges to vary by a factor

of 3 or more (e.g., Fig. 8) and can result in strong surface backscattering (clutter) from very long ranges (e.g., Fig. 6), which may degrade radar performance in a number of ways. Furthermore, multipath fading, caused by interference between direct and reflected propagation paths, may result in dropped tracks on low-to-moderate altitude targets.

Over the sea, low-flying targets, which are normally hidden from the radar until they come above the Earth's horizon, present a stressing threat to shipboard weapon systems because they are quite close by the time they are detected. Furthermore, the radar's actual performance in these situations is very sensitive to atmospheric refractivity conditions, and before 1980 methods to analyze and predict these effects did not exist. Earlier versions of the Tropospheric Electromagnetic Parabolic Equation Routine (TEMPER) were developed to answer this need for the Aegis system[3–6] and were used in conjunction with the newly developed APL AN/SPY-1 FirmTrack simulation to analyze radar and missile illuminator performance. In addition to the development of TEMPER and FirmTrack, atmospheric measurement instrumentation and techniques were developed to characterize the refractive conditions. This work is described in a companion article by Rottier et al. in this issue. That article also serves as a good introduction to the types of atmospheric refractivity conditions that are typically encountered over the oceans.

The combination of propagation modeling, radar simulation, and environmental measurement and characterization provided the first capability to quantitatively reconstruct radar performance during Navy tests. This capability served the important role of relating observed radar performance to the system specifications, which are typically based on "standard" refractive conditions. This analysis capability also provided, again for the first time, an understanding of the phenomena causing degradations in radar performance. The next major challenge to radar performance analysis in general, and propagation modeling in particular, appeared as new missions and tactics brought the formerly "blue-water" Fleet in close proximity to land. Irregular terrain introduces many large, nonuniform effects in radar systems, including target shadowing, huge backscatter (clutter) returns, and sensitivity to the ship's position relative to land. Developing a capability to model radar propagation and performance near and over land became a priority when actual radar performance was observed to be highly variable and often degraded in littoral regions. These effects spurred development of improvements in existing systems, such as the AN/SPY-1D, which is being upgraded to the AN/SPY-1D(V), and new designs for future radars, such as the Multi-Function Radar (MFR). A high-fidelity, terrain-capable propagation model was required to support the design and evaluation of these systems. Recent upgrades to TEMPER were designed to provide this capability.

There have been several approaches to representing radio-frequency propagation in the atmosphere, including geometric optics (ray tracing), normal mode theory, and physical optics (spherical-Earth diffraction and multipath models). Each of these approaches has well-documented limitations in accuracy and/or applicability relating to allowable frequencies, diffraction effects, terrain modeling, and complexity of atmospheric refractivity. These restrictions severely limit the utility of such methods for high-fidelity applications, such as predicting the radar detectability of low-altitude targets in realistic environments. The development of efficient numerical solutions of the parabolic wave equation (PE) offered a major breakthrough in electromagnetic propagation modeling by allowing accurate calculations for realistically complicated refractive environments.

The PE is a forward-scatter approximation to the full Helmholtz wave equation and inherently includes effects caused by spherical-Earth diffraction, atmospheric refraction, and surface reflections (i.e., multipath).[7] As a direct numerical evaluation of the forward wave equation, PE-based models avoid most of the limitations associated with the other modeling approaches mentioned because of the lack of simplifying assumptions. Advanced versions of PE models also include impedance boundaries, rough surfaces, complicated antenna patterns, irregular terrain, atmospheric absorption, and/or other scattering phenomena. PE methods have become the preferred propagation modeling approach for many Navy applications covering a wide range of frequency and propagation geometries for radar, communications, weapon, and electronic support measures systems.

The PE method was first introduced in the 1940s by Fock.[7] At that time the method could be applied only to simple geometries and refractive conditions. In the early 1970s a spectral method, called the Fourier split-step (FSS) method, was applied to the parabolic equation[8] to predict underwater acoustic propagation. With this improvement, practical application of the model to more complicated atmospheres and surface boundaries became possible. In the early 1980s, the FSS-based PE model first began to see application to radio-frequency propagation, resulting in the EMPE model.[9] Since then, several advances have increased the accuracy, speed, and flexibility[3–6] of the basic PE method that is the heart of TEMPER. This article discusses the advances made in the last few years that culminated in the release of TEMPER Version 3.10 to the propagation community.

A number of PE-based and PE-hybrid models exist today. These include Radio Physical Optics (RPO),[10] Terrain Parabolic Equation Model (TPEM),[11] Advanced

Propagation Model (APM), and Variable Terrain Radio Parabolic Equation (VTRPE),[12] all created by the Space and Naval Warfare Systems Command Systems Center in San Diego, and the PCPEM and TERPEM models, which were developed in the United Kingdom. The APL model of this class, TEMPER, is regarded as the benchmark PE model in the U.S. Navy propagation community. Several algorithms originally developed for TEMPER have been integrated into other models like APM and TERPEM. Reference 13 provides an excellent discussion of the history surrounding the development of these PE models as well as the interchange among organizations that has advanced the state of propagation modeling.

TEMPER has found use in numerous U.S. Navy and other Department of Defense programs in addition to the Aegis Program for which it was primarily developed and from which the primary funding originated. Some of these beneficiaries include the Cooperative Engagement Capability (CEC), DD 21, Multifunction Radar/Volume Search Radar (MFR/VSR), NATO Sea Sparrow, Ship Self-Defense System, and High Frequency Surface Wave Radar programs. As a result, the TEMPER model is, or has been, used by more than 30 government agencies, commercial contractors, and universities across the country.

Within the Aegis Program, TEMPER is an important part of the APL SPY-1 FirmTrack model, which provides the highest-fidelity representation of that radar system's performance against a wide variety of threats. Also, TEMPER has been optimized, along with Firm-Track, for near–real-time use in the Shipboard Environmental Assessment Weapons System Performance (SEAWASP) shipboard Tactical Decision Aid. SEAWASP is currently a prototype system on USS *Anzio* (CG 68) and USS *Cape St. George* (CG 71). (See Ref. 14 and the article by Sylvester et al., this issue.)

PE MODELING ADVANCES

This section provides some detailed information about improvements made to the TEMPER program in the past 5 years. While some of these changes are specific to the TEMPER interface, others have significantly advanced the state of the art for propagation modeling.

General Improvements

Several general improvements have been made to the TEMPER model that warranted incrementing the version number from 2 to 3. A number of these changes are categorized as recoding, to allow for such capabilities as dynamic array sizes and more efficient calculations. Some of these improvements are discussed in Ref. 15.

Another change to the model was the addition of new source-field types to augment the small original set.

These source types include a built-in plane wave, which has been particularly useful when comparing TEMPER with other models. Also, the generic asymmetric pattern type was added to provide the most flexibility when specifying a generic (i.e., non-symmetric) antenna pattern.

Another improvement relates to how the wide-angle propagator in the PE model affects the source field. Kuttler[16] found that this propagator distorted the source fields as they were previously defined and that the introduction of a "correction factor" into this initial field would counter this distortion as the field propagates. The result of this work allows TEMPER to more accurately represent fields that propagate at steeper angles.

Another improvement that relates to wide-angle propagation is the use of filters in both real and transform spaces. TEMPER mitigates against energy reflections from the upper numerical boundary by periodically applying a filter in both the real and transform spaces. TEMPER 2 used the same filter in both domains, and the filter coefficients were represented by single-precision values. TEMPER 3 now uses double-precision coefficients, which significantly reduce numerical noise levels. In addition, the transform-domain's filter (termed the "p-space filter") has been widened from the previous limit of around 49° (relative to the horizontal direction of propagation) to approximately 60°. This increase in available "problem space" reinforced the Linear Shift Map terrain method (described later), as it allows the model to include a greater amount of terrain-scattered energy.

Other changes to the TEMPER model can be categorized as improvements to the previous interfaces. For example, a number of new input parameters afford greater control over the program, while a significant amount of logic has been coded into TEMPER to prevent incorrect parameter combinations. TEMPER 3 can automatically choose some parameters if the user has no specific requirement. Also, the main output files from TEMPER have been significantly updated. The Print File now includes much more diagnostic information than in the past. The binary Field File includes a great deal more information in its header record than before; it also includes grazing angle and terrain height information with the propagation factor data. TEMPER now offers two compression schemes to reduce the file size by factors of 2 and 4, although at the expense of some fidelity.

In summary, many of the improvements to the TEMPER code have resulted in an easier-to-use model that provides a more accurate field solution. As evidence of its utility, more than 100 people now use TEMPER 3 in approximately 30 military installations, DoD commercial contractors, and universities, including many users within APL.

Grazing Angle Estimation

There is no question that the most used and important TEMPER product is the propagation factor data. This quantity is critical to the implementation of the radar range equation for low-elevation-angle propagation. Recent attention within the Air Defense Systems Department has been directed toward surface clutter modeling, which requires not only propagation factor data near the surface but also the local grazing angle.[17,18] This is the angle at which the incident field energy strikes the surface. To account for rough-surface effects on propagation, TEMPER also requires the grazing angle at each range step. TEMPER uses this value to calculate the Miller-Brown rough-surface reduction factor.[19] This factor reduces the values of the smooth-surface reflection coefficient used in the discrete mixed Fourier transform (DMFT) method of accounting for field interaction with the lower boundary.

Simple geometry provides a straightforward technique for calculating grazing angles. TEMPER is capable of both flat- and spherical-Earth calculations. Geometric methods are only useful for very simple atmospheres having linear refractive gradients and cannot be used for complicated terrain boundaries.

An alternate method is geometric optics (GO), which can be used in complicated refractive environments and can account for terrain. TEMPER 2 employed a separate, external program to compute this type of angle.[20] The problem with this approach was twofold: (1) the potential for errors associated with how the external GO program and TEMPER handled the necessary refractivity interpolations and (2) ensuring that both programs used the same physical and electrical parameters. TEMPER 3 now has a variant of GO code included within the program, which eliminates these concerns.

Although GO codes are certainly capable of determining grazing angles for terrain surfaces, they can only do so for directly illuminated areas. That is, a pure GO method cannot account for diffraction. An alternative that performs quite well in this case is spectral estimation (SE), more specifically, an SE method that uses the Multiple Unknown Signal Identification and Classification (MUSIC) algorithm.[21] TEMPER can use the SE/MUSIC algorithm in all cases, but it has been demonstrated that this method performs poorly in evaporative ducting environments.[22] This limitation is caused by the strong refractive gradients associated with evaporative ducts. These gradients drastically refract the field within the MUSIC algorithm's sampling window, leading to errors in the spectral estimation. Finer resolution in altitude mitigates these errors but has the undesirable side effect of large transform sizes and consequently long computation times. As a result, it is impractical to use the SE/MUSIC technique for evaporative ducts.

TEMPER 3 now makes use of all three of these grazing angle estimation methods. For very steep propagation angles (i.e., larger than about 1.5° and close to the emitter), simple geometry is used. This is acceptable because refractive effects on propagation are negligible above this limit. For over-sea portions of a propagation path, the GO method is used because it performs better than the SE method in all refractive environments. For any terrain along the path, the SE/MUSIC method is used. The SE/MUSIC evaporation duct limitation is not a concern because terrain tends to break up any evaporative duct within a short distance from the shoreline. In cases where terrain shadows a portion of an ocean path, the SE/MUSIC result is used until the SE grazing angles fall below those values determined by the GO method. In this way, the grazing angles for terrain-diffracted fields are adequately captured. Figure 1 illustrates the application of this procedure to a mixed land–sea propagation path in the presence of a moderate evaporation duct. Figure 1b shows the surface height profile, which is a simple "terrain wedge" with a 3° slope; Fig. 1a provides the results of the SE, GO, and automatically combined grazing angle estimation. Note how the SE method significantly underestimates the grazing angles over most of the sea path; however, this method does an excellent job of detecting those angles on the illuminated face of the wedge, quickly diminishes to small values on the shadowed face, then accurately provides the diffraction-induced grazing angles over an appreciable portion of the shadowed sea surface. On the other hand, the GO method does well in the directly illuminated sea region but ignores the terrain altogether.
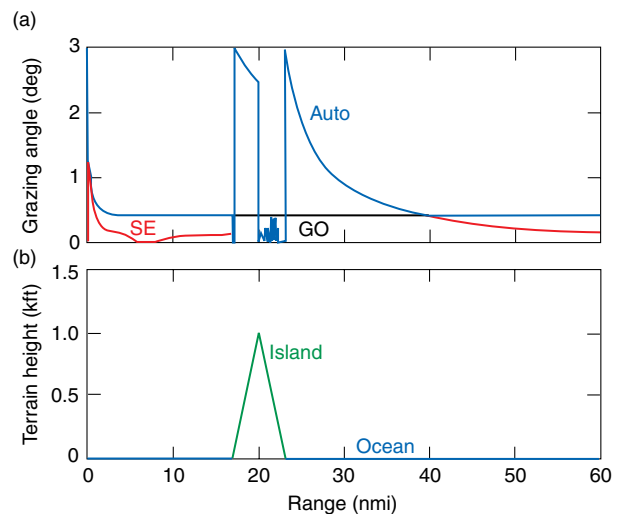

Figure 1. Illustration showing how the automated grazing angle algorithm handles mixed terrain/refractivity conditions. (a) The resultant grazing angle profile is given by the blue line (Auto = automatically combined, GO = geometric optics method, SE = spectral estimation method); (b) the ocean/terrain boundary.

TEMPER automates this whole process so that a user need not be an expert in deciding which of these methods should be used together. For a given case, TEMPER first looks to see if there is terrain in the problem and whether a strong, negative refractive gradient (indicative of an evaporative duct) is present in the refractivity file. Depending on which of these conditions exists (including whether grazing angles are either required by the rough-surface model or requested by the user for later use), TEMPER will decide which algorithms must be used and then will automatically splice together the appropriate results for each region. A summary of the methods that were used in constructing the grazing angle array is provided in the Print File.

As noted in the previous section, the grazing angles are now included in the binary Field File along with the propagation factor data. In addition, TEMPER can create a separate ASCII grazing angle file for other uses.

Including Terrain Effects

Another significant improvement in recent years is the method by which TEMPER accounts for general terrain surfaces. TEMPER 2 has a single, simple method that essentially zeros the field from the terrain height down to mean sea level before propagating the solution to the next step. This method is termed the "knife-edge" (KE) method because it resembles propagation over a series of perfectly conducting knife edges. This method is extremely simple to implement and actually provides a remarkably reasonable result for diffracted fields when compared to analytical solutions for propagation over single and multiple knife edges.

While the KE method does quite well with terrain diffraction, it cannot represent the effects of scattering by terrain surfaces. Donohue and Kuttler[23,24] recently provided an alternate method that maps the complicated terrain boundary onto a flat surface through a combination of vertical shifts, phase steering, and surface impedance modifications. This method, called the Linear Shift Map (LSM) method, expands upon earlier work by Beilis and Tappert.[25] It provides reasonably accurate results for terrain slopes that do not exceed about 14°. Since that work was published, an additional limit on the *change in slope* has been observed, and this limit is dependent on the chosen problem angle (transform space bandwidth) for a particular case.

Figure 2 shows TEMPER coverage diagrams for the KE and LSM methods. Note how the LSM method provides forward-scattered fields that the KE method cannot represent.

Improved Numerical Stability

One of the most recent improvements to the TEMPER model addresses a longstanding numerical instability. This problem caused errors in the TEMPER
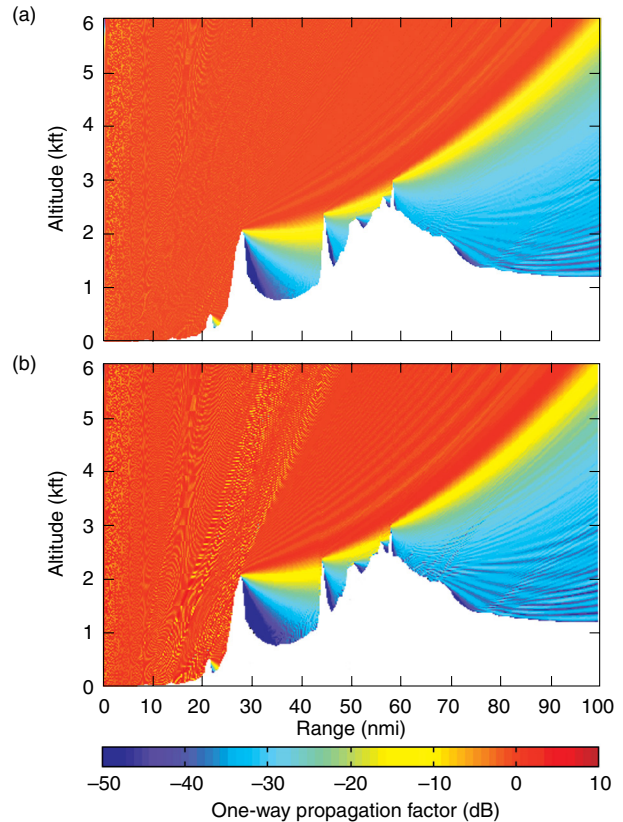

Figure 2. L-band examples of (a) the knife-edge terrain method and (b) the Linear Shift Map terrain method.

solution that were manifested as unrealistically large propagation factor values in some portion of the output. While it is difficult to ascertain the parameter combinations that cause the instability, it generally arises when rough-surface calculations are performed at high frequencies and/or roughness values. To some degree, the surface electrical parameters also affect the instability.

This problem occurred in the DMFT method, which introduces an auxiliary function to effectively halve the number of transform calculations. This auxiliary function involves a second-order difference equation, which uses a second-order, centered discretization of boundary-condition derivatives. Alternate numerical formulations of the auxiliary function were investigated, one that uses a first-order forward difference and another that uses a first-order backward difference. These first-order equations turned out to be less susceptible to numerical instabilities than their second-order counterpart.[26] As an additional benefit, where one of the first-order equations is unstable, the other is generally found to be stable. As a result, one can almost always find a combination of these two first-order methods that works.

A secondary benefit of using the first-order difference equations is a reduction in the number of floating-point operations required in these algorithms. The

original second-order equations require two back-solving operations per range step to arrive at a solution, while the new first-order equations require only one back-solving operation for the same range step. As a result, TEMPER's new algorithm is slightly faster than its predecessor.

The cost of this improvement in stability and computation time is an inherently less accurate representation of the boundary condition, owing to the lower-order approximation. However, when the TEMPER altitude step size is kept reasonably small, the difference between first- and second-order solution methods is negligible for microwave frequencies. For the high-frequency through ultra high-frequency bands, the first-order solutions give unacceptable errors when compared to the second-order solution. The original second-order method is retained for these lower frequencies, where this method rarely exhibits the instability problem.

Thus, a carefully selected combination of both first- and second-order difference equations is now applied across TEMPER's valid frequency range of 10 MHz to 20 GHz, providing generally faster calculation times and better numerical robustness than earlier versions of TEMPER.

Application to Sectors

Recent attention has been focused on modeling propagation conditions over wide areas (sectors) for shipboard sensor applications. These sectors may contain terrain with widely varying relief. Of particular interest is the land and sea clutter cross section presented to such systems. TEMPER is a two-dimensional (2-D) propagation model and thus cannot model effects such as terrain-influenced out-of-plane scattering, diffraction, and depolarization. With those limitations in mind, TEMPER can still provide useful "first-order" terrain effects for wide-area situations by combining the 2-D results for multiple bearings.

One observation is that the refractive environment near the ship is independent of azimuth. With this assumption, TEMPER calculations close to the ship are redundant in azimuth out to a certain range. A recent update to TEMPER includes the ability to initialize a new TEMPER run using complex field information calculated from earlier TEMPER calculations. With this approach, a single sea-surface calculation covers all bearings up to the range where the environment changes. Then, at that range, the sea-surface case can be used to "restart" a new TEMPER calculation on each particular bearing.

Figure 3 illustrates this concept for a ship located some distance offshore. First, a single terrain-free TEMPER run is performed out to a maximum range of interest, R_f, and at certain intervals (R_i, with $i = 1, 2, \ldots, N$) the complete complex field solution is stored. These intervals are
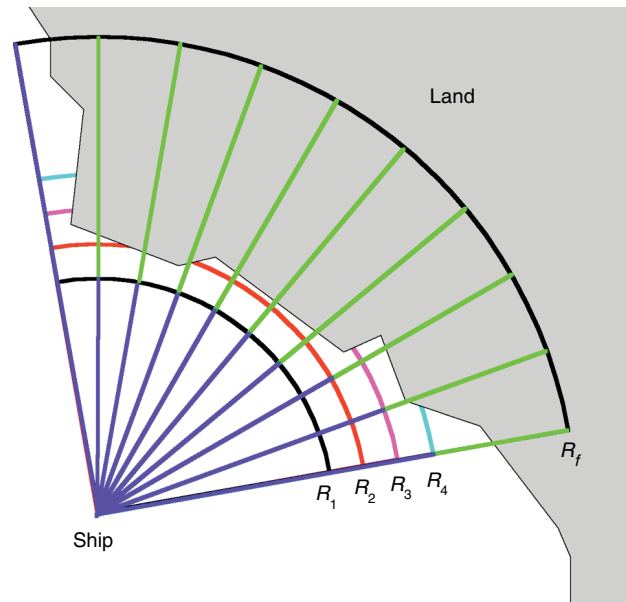

Figure 3. Illustration showing the use of multiple two-dimensional solutions to represent three-dimensional regions. (R_f = maximum range of interest, R_i = range at interval i.)

somewhat arbitrary, but if there are too many intervals, the size of the Storage File may become larger than the Field File, negating the reason for this method. Then on a particular bearing, TEMPER initializes a new run at the location, R_i, where the "open ocean, homogeneous environment" assumption is no longer valid. This new run begins by extracting the stored "base" field at range R_i. TEMPER then propagates this field out to the maximum range R_f using the bearing-specific environment. The procedure is repeated for all bearings of interest, potentially saving a great deal of computation time and storage space. This modeling procedure is being used in an effort to integrate the powerful capabilities of the TEMPER model into a program that calculates surface and volume clutter cross sections, including propagation effects, for generic radar systems. This Integrated Clutter Model, a recently launched effort within the Air Defense Systems Department, seeks to combine the TEMPER propagation model with accepted models for sea and land clutter as well as with newly developed models for rain, dust, biological, and discrete clutter sources.

Figures 4 through 6 provide an example of the application of this restart technique. Figure 4 shows a terrain map constructed from the Digital Terrain Elevation Database for a notional ship located in the middle of the Arabian Gulf, approximately 100 km north of Qatar. In this example there are terrain heights in excess of 3 km toward the northeast and comparatively moderate terrain to the south and west. Figure 5 shows a refractivity profile constructed from balloon-sonde measurements made aboard USS *Lake Erie* (CG 70) in October 1999 at the position shown in Fig. 4. For the purpose of demonstrating the restart method, this profile is assumed
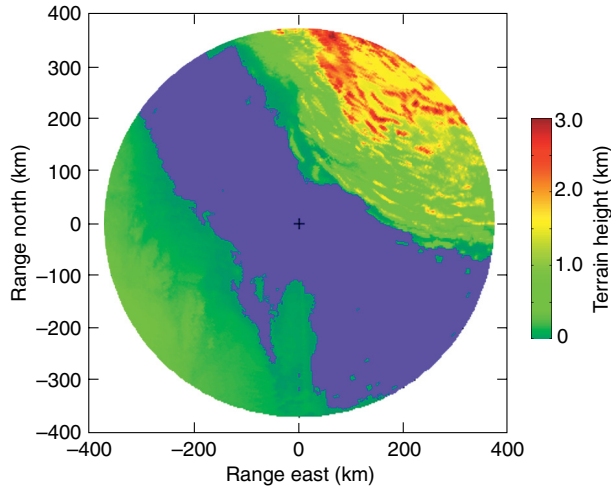
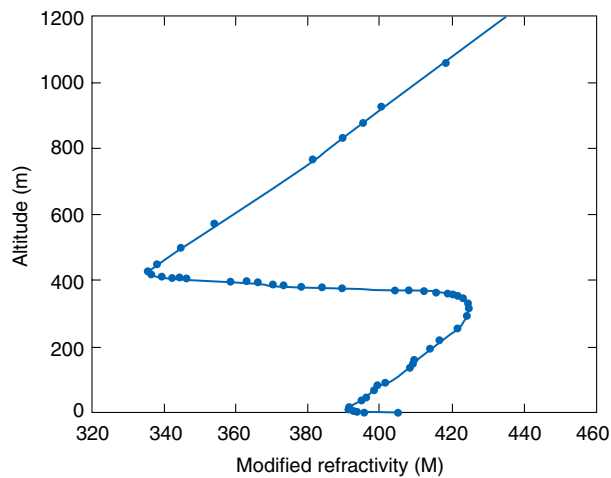**Figure 4.** Arabian Gulf terrain map as an example of the "restart" method.

Figure 5. Measured refractivity profile from the Arabian Gulf in October 1999.

Figure 6. Comparison of propagation factor maps for (a) standard atmosphere and (b) measured refractivity conditions.

to be valid for the entire region. It is worth noting that this assumption is generally not true, especially as the range from the ship increases and as the propagation path transitions from sea to land.

The TEMPER program was applied to 360 bearings originating from the center of Fig. 4, but only those portions of each bearing with terrain are actually calculated. For the remainder of those paths, a base case is used. Figure 6 shows the TEMPER calculation results for a standard atmosphere (Fig. 6a) and the measured refractivity profile (Fig. 6b) in Fig. 5. The plots show the one-way propagation factor, in decibels, at an altitude of 1.2 m above the sea or terrain surface for an S-band emitter. The effects of surface-based ducting are dramatic in most areas except in the northeast, where coastal mountains have blocked the ducted energy. For this example, the restart method saved about 45% in
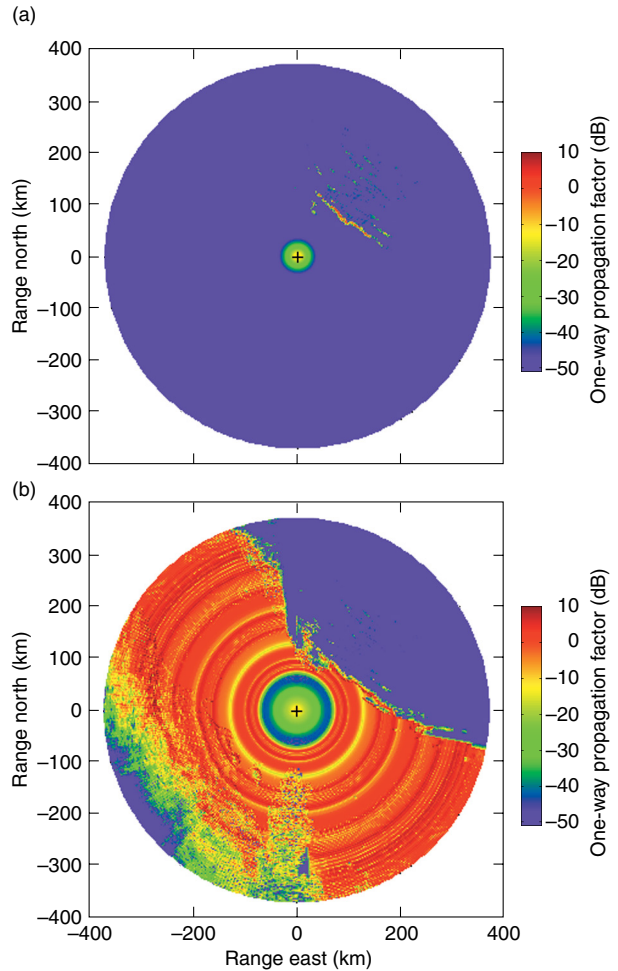
computation time and 55% in data storage compared to calculating each bearing entirely.

VERIFICATION, VALIDATION, AND ACCREDITATION

During the development of the model, TEMPER has been engaged in several verification and validation (V&V) efforts. V&V methods included comparison with other models in their applicable parameter spaces, data collections at field tests devoted to propagation experiments, and radar system field-testing against live targets.

Comparisons of TEMPER with other models are well documented.[27] These other models include waveguide-mode calculations, spherical-Earth diffraction models, ray optics methods, and moment-method techniques. In addition, TEMPER has been compared with other PE-based and hybrid propagation models through participation in several organized propagation modeling workshops.[28] In all cases, TEMPER compared very favorably with these models in their regions of validity.

On several occasions, well-organized propagation-oriented field tests in the mid-Atlantic and Puerto Rico areas have provided valuable data with which to make comparisons. When sufficient meteorological data were collected to adequately characterize the environment, TEMPER-modeled results compared very favorably with received signal and/or surface clutter power measurements.[27] Figure 7 provides an example comparison from a 1986 propagation test in the Wallops Island, VA, area. The red curve is a TEMPER result for a 4/3-Earth (standard atmosphere) environment, the green curve is the TEMPER result using the measured environmental data, and the blue curve is the measured received power.

TEMPER has also undergone extensive V&V as part of the FirmTrack radar system performance model. In this case, the comparison to be made is the measured versus modeled final firm track range for a radar system against a particular target in a given environment. The firm track range is defined as the range from the ship at which a given target will be in track a certain percent of the time. Over the last two decades, APL's Theater Systems Development Group has developed this radar model to represent the functions and processing methods of the AN/SPY-1 class of radars (i.e., the radar class associated with the Aegis Weapons System). A key part of the FirmTrack modeling process for low-altitude targets is the propagation factor result from TEMPER. The interdependence of TEMPER and Firm-Track means that V&V results of this kind assess the validity of TEMPER's propagation factors, albeit indirectly. Once again, in cases where adequate, timely environmental data were collected, the combined TEMPER/FirmTrack-modeled firm track range compared very well with measured data. Further discussion on this modeling aspect and an example that demonstrates the agreement between modeled and measured tracking performance is provided in the article by Sylvester et al. in this issue.

This extensive V&V effort spanning the last 15 years has resulted in the accreditation of the TEMPER model by several U.S. Navy programs, including the MFR Program (PMS-500), Cooperative Engagement Capability (CEC) Operational Evaluation (OPEVAL) analysis (PMS-400 and PMS-465), and the DDG 51 Live Fire Test and Evaluation (LFT&E) Program (PMS-400).

SHIPBOARD APPLICATION

TEMPER development began as an engineering model and was not initially intended for use in operational systems. It soon became apparent that such a modeling capability would be valuable onboard operational Navy ships for near–real-time radar system performance assessment and resource management. An effort to provide this capability to the Navy culminated in the Shipboard Environmental Assessment Weapons System Performance (SEAWASP) system, a prototype tailored to the AN/SPY-1 radar on USS *Anzio* and USS *Cape St. George*.[14] In this case, the TEMPER model has been tailored to accept inputs from the Environmental Assessment Subsystem, to efficiently represent the AN/SPY-1 radar physical and electrical parameters, and to provide streamlined output for subsequent use in an optimized version of FirmTrack.

The SEAWASP system has gained wide acceptance by the ships' crews and has demonstrated the importance and need for accurate environmental assessment for all shipboard sensors. As a result of this system's deployment, efforts are currently under way to provide an updated environmental assessment system in the form of the Shipboard Meteorological Oceanographic Observation System (Replacement). While there currently is no program to transition the weapons system performance subsystem into an operational system, efforts are under way to reconcile this approach with other methods that are being proposed in the Naval Meteorology and Oceanography Center and operational communities.

FUTURE MODELING DIRECTIONS

Although the current TEMPER implementation is mature, there are still areas to be explored. As the newer capabilities are applied to increasingly complex littoral environments, it is certain that fine-tuning of the grazing angle and terrain methods will be required. In addition, several projects are under way within APL that seek to improve our understanding of propagation through real environments and over complex terrain.

An effort recently began creating a fully polarimetric, three-dimensional (3-D) model for propagation over 2-D terrain. The current 2-D TEMPER program is only capable of representing the effects of one-dimensional surfaces. The inherent limitations of a 2-D model are that it cannot account for out-of-plane scattering or diffraction caused by real terrain or out-of-plane refraction caused by azimuthally dependent environments. A 2-D model also cannot deal with depolarization caused by the environment or surface.
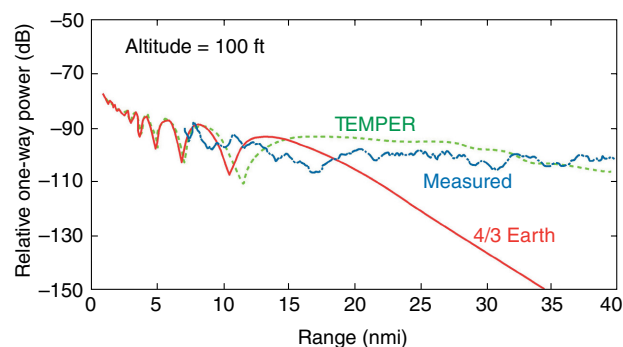

Figure 7. Comparison of modeled and measured power levels from an October 1986 test in the Wallops Island, VA, area.

The impetus for a 3-D model is to provide a benchmark against which the current 2-D codes can be compared. Since the 3-D model can account for energy that may scatter and diffract around the terrain, it is thought that this might explain observed discrepancies between measured clutter power levels and simulated clutter power derived from 2-D models. Studies of this type will improve the state of land clutter modeling.

Another area where 3-D propagation modeling may contribute is ship signature modeling. The problem is centered on how well a low-flying anti-ship cruise missile may view a surface ship in a clutter background. This is a topic of great interest to efforts like DD 21, where the effectiveness of reducing the ship signature may in part depend on the environment in which it operates. Depolarization and out-of-plane scattering may limit the effectiveness of ship signature reduction methods as the resulting radar cross section approaches that of the clutter background. Two-dimensional propagation models cannot account for these effects on their own and therefore cannot be used to assess the sensitivity of ship design to these effects.

The 3-D nature of the problem precludes use of the Fourier methods that have worked so efficiently for 2-D propagation models like TEMPER. The most efficient method available for the 3-D problem is implicit finite differences. Both the 2-D Fourier methods and the 3-D implicit finite differences methods are marching solutions; beyond that, the methods are completely different. Early results are promising; for example, 3-D propagation results have already been achieved for simple objects like buildings and smooth Gaussian hills. Eventually the model will be expanded to handle general terrain surfaces.

Another current effort intends to improve how propagation models account for rough ocean surface reflection. TEMPER's current approach uses an empirical model that reduces the smooth-surface reflection coefficient, thereby reducing the coherently reflected field. The limitation of this method is that the empirical model's assumptions break down at high sea states and grazing incidence. The amount of error in this method is currently unknown, however, because it is extremely difficult to collect data to support such a study. A numerical study is under way that will attempt to quantify these errors. This effort will compute exact scattering results for realistic ocean surface realizations by accelerated moment method techniques, then ensemble average over many realizations to determine the average scattered field as a function of grazing angle, frequency, polarization, and surface conditions. This is a tremendous computational challenge, requiring supercomputing resources for results from a single surface realization. However, recent acceleration techniques are making this study possible with available DoD supercomputing resources. The end result will be an improved model for representing rough-surface effects in 2-D propagation models.

An investigation that has just begun is the application of the propagation model to wideband (e.g., pulsed) applications. TEMPER and other PE models provide inherently single-frequency or monochromatic solutions. This type of solution is adequate for narrowband (long pulsewidth) and continuous wave systems, but with new radar designs considering the use of short pulsewidths the narrowband assumption may not hold. A candidate approach uses Fourier synthesis of several single-frequency solutions to simulate wideband propagation.

SUMMARY

In recent years many improvements have been made to the TEMPER propagation model, a number of which are generally applicable to any PE-based model. Improved grazing angle estimation is important not only to field propagation but also to clutter models that apply the TEMPER grazing angles directly. The modeling of terrain effects has also progressed markedly. Using these grazing angle and terrain modeling methods, TEMPER can provide an excellent representation of field propagation in littoral environments. The improvement in numerical robustness afforded by a slight reformulation of TEMPER's DMFT allows the model to be used at higher frequencies and sea states than ever before possible. These recent improvements have also helped in the effort to provide wide-area, propagation-modified surface and volume clutter data for site-specific radar system modeling applications.

TEMPER has been recognized as the benchmark propagation model by the Navy community and has received accreditation from several programs. TEMPER has also been incorporated into the shipboard prototype SEAWASP, providing critical propagation information to Aegis AN/SPY-1 performance models on USS *Anzio* and USS *Cape St. George*.

Future efforts include 3-D model development for more accurate representation of depolarization and out-of-plane scattering, diffraction, and refraction. Also, improvement of TEMPER's rough-surface modeling procedure is anticipated through the study of rigorous moment method calculations.

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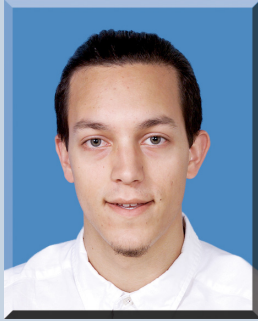
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