Development and Use of Electromagnetic Parabolic Equation Propagation Models for U.S. Navy Applications

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The U.S. Navy has been developing models to describe and predict electromagnetic propagation in the lower atmosphere for many years, and these models have been used in conjunction with system simulations to evaluate operational system performance with excellent success. Current capabilities in electromagnetic propagation modeling for the Navy are the result of cooperation between several organizations both inside and outside the Navy community. Currently, several propagation models are available to prospective users, which has resulted in some confusion regarding validation, certification, and accreditation. The objective of this article is to explain the history, evolution, and intended applications of the various models, as well as to address some of the current issues in model validation and certification. Recommended guidelines for model selection are also presented.
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INTRODUCTION

The U.S. Navy began working to understand and predict low-elevation electromagnetic (EM) propagation in the troposphere 50 years ago (e.g., Ref. 1). The review article by Hitney et al.[2] provides several references documenting progress in modeling EM propagation and its impact on ship systems performance through the early 1980s. At that point, practical methods for representing propagation included geometric optics (ray tracing), normal-mode waveguide theory, and spherical-Earth multipath and diffraction models.[3] Each of these methods has well-documented limitations in accuracy and/or applicability relating to allowable frequencies, diffraction effects, terrain modeling, and restrictions in refractivity complexity. These restrictions have often severely limited the utility of such models for high-fidelity applications, such as predicting the radar detection of low-altitude antishipping missiles.

The development of efficient numerical solutions of the parabolic wave equation (PWE) offered a major breakthrough in EM propagation modeling by allowing accurate calculations for realistically complicated refractive environments. The PWE is a forward-scatter, narrow-angle approximation to the full Helmholtz wave equation[4,5] and inherently includes effects due to spherical-Earth diffraction, atmospheric refraction, and surface reflections (i.e., multipath). Advanced PWE models may also include impedance boundaries, rough surfaces, complicated antenna patterns, irregular terrain, atmospheric absorption, and/or other scattering phenomena (e.g., Refs. 4–10). PWE-based methods result in less complicated propagation models in the sense that direct numerical evaluation of the wave equation eliminates the need to use different approximations and algorithms for different geometries (e.g., multipath interference, transition, and diffraction regions), or for different frequency regimes (e.g., surface-wave formulation for HF and simple Fresnel reflection theory for higher frequencies). Also, there is no need to express the solution as a complicated sum of normal or coupled modes.

For these reasons, PWE methods have become the preferred propagation modeling approach for many U.S. Navy applications covering a wide range of frequency and propagation geometry for radar, communication, weapon, and electromagnetic support measures systems. PWE models are currently used in trade-off studies and design evaluations,[11] analyses of experiments and at-sea tests,[12–15] operational performance assessment,[16–18] and mission planning programs.[19] It is likely that they will be used in acceptance testing and other phases of the Navy's acquisition process in the near future.

The considerable propagation modeling capability that currently exists within the Navy's EM community is due largely to the cooperation and interaction that have occurred between various laboratories, including (but not limited to) the SPAWAR Systems Center San Diego (SSC-SD) (formerly Naval Command, Control, and Ocean Surveillance Center RDT&E Division, NRaD), The Johns Hopkins University Applied Physics Laboratory (APL), the Naval Postgraduate School (NPS), the Naval Research Laboratory's Monterey contingent (NRL/Monterey), and Rutherford Appleton Laboratories in the United Kingdom (RAL). The productive interchanges between these organizations are typified by two PWE workshops hosted by SSC-SD in 1989 and RAL in 1992, as well as by the Electromagnetic Propagation Workshop held at APL in 1995.[20] Similar, less organized exchanges have taken place at certain NATO AGARD (Advisory Group on Aerospace Research and Development) symposia and other forums focused on propagation. On these occasions, ideas, calculations, and algorithms were presented and discussed openly among the participating groups, and many comparisons between models and approaches were conducted. The net result has been a merging of approaches and accelerated progress in propagation model development for the Navy. It is hoped and expected that such cooperation between these laboratories will continue in the future.

The aforementioned activities have produced several PWE-based models, in various versions, over the past several years, resulting in occasional confusion regarding pedigree, accuracy, features and capabilities, and validation and verification. Generally, the various models have been developed for different applications, which in turn have different requirements for computation speed, model features, and accuracy. It is important to understand these attributes when selecting a model for a particular use. Unfortunately, the applications for which models have been certified or validated are sometimes forgotten or ignored, resulting in the misapplication of these models.

The purpose of this article is to present some historical perspective on the development and use of PWE-based tropospheric propagation models within the Navy, as well as to address some application, standardization, and certification issues. Current thrust areas in model development and application are also mentioned.

GENERAL CHARACTERISTICS OF PWE MODELS

Before continuing, it is helpful to describe some of the general characteristics of PWE codes that set them apart from other propagation modeling techniques. The PWE is an initial-value problem amenable to numerical solution using marching methods that begin at or near the antenna of interest and march out in range and/or altitude. It is thus necessary to specify an initial field solution at a reference range (or altitude), as well as boundary conditions in the other dimension. The most common type of PWE model marches in range, calculating the field along a vertical strip during each range step. It is also possible to march in altitude using an initial solution specified in range at a reference altitude.[21] As described later, there are at least two popular numerical methods for solving the PWE, but they both involve stepping in range (or altitude) and require the same kind of initial solution and boundary conditions.

In contrast to some other types of propagation models (e.g., geometric optics and spherical-Earth diffraction models), PWE methods naturally produce a range–height grid of calculated values; this characteristic has both advantages and disadvantages. The primary advantages are (1) the user can examine many different trajectories through the output data matrix without rerunning the model, and (2) the data for range–height color-modulated plots (e.g., Fig. 1) are an automatic by-product. However, if any system or environmental parameters are changed (e.g., frequency, antenna height, antenna pointing direction, refractive conditions, etc.), the model generates the entire output grid again with the new parameters. That is, one cannot simply go to a downrange point and calculate a value; the model must "march" to that point from the beginning. For this reason, speed comparisons between PWE and other methods should be made in the context of a particular type of application. For example, although PWE codes can be quite fast, they generally remain too computationally burdensome for use in a time-step tracking simulation in which the modeled antenna pointing direction is changing frequently. On the other hand, other types of models often take substantially longer than PWE-based codes to calculate a large grid

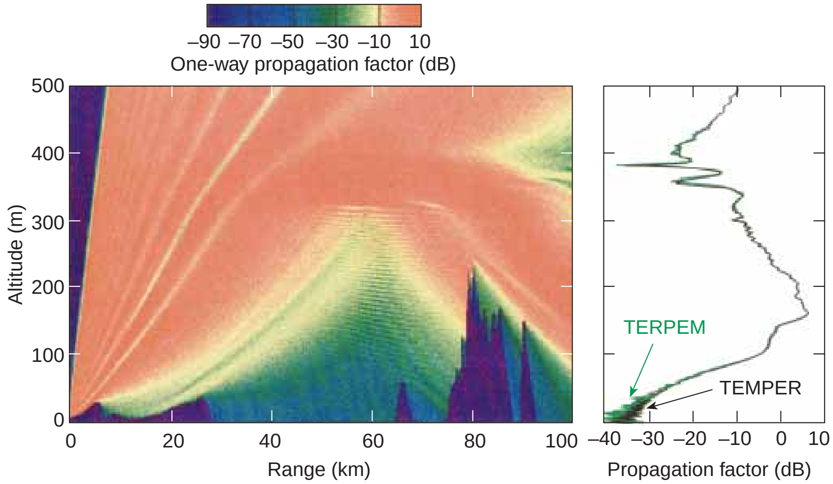

Figure 1. Electromagnetic Propagation Workshop, Case 9: 3 GHz, 10-m antenna, 400-m surface duct over terrain, 100-km range. (TEMPER = Tropospheric Electromagnetic Parabolic Equation Routine, TERPEM = hybridized Terrain Parabolic Equation Model.)

of values for range–height plots. In any case, the PWE approach is at present the only method capable of handling realistically complicated atmospheric conditions.

The two most popular methods of evaluating the PWE are the Fourier split-step (FSS) solution and implicit finite difference (IFD) equations. The former method employs an approximate solution to the PWE in the Fourier transform domain (spatial frequency space), whereas the latter converts the PWE to a system of coupled difference equations that is solved via matrix inversion techniques. Both methods solve for field values at a given range and up to the maximum altitude based on the field values at the previous range. Generally, the stability of the FSS algorithm allows the use of larger range increments (which means fewer steps) than the IFD approach, but it is easier to implement complicated boundary shapes and conditions with IFDs. Although there are situations in which the IFD method is desirable, the FSS has thus far been the most successful, particularly in the EM microwave regime where propagation distances are typically thousands of wavelengths. The most frequently used PWE models in the U.S. Navy community are of the FSS variety.

Other typical features for PWE codes include (1) the use of a Leontovich impedance boundary condition to represent the conductivity, permittivity, and fine-scale roughness of the Earth's surface, and (2) the calculation of an initial solution using the Fourier transform relationship between an elevation-plane antenna radiation pattern and a line-source distribution.[5,22] Also, many PWE developers have recently gravitated toward the use of algorithms based on a terrain-flattening coordinate transformation[23] for representing propagation over terrain.

Perhaps the greatest "danger" associated with PWE models is that when they fail, they often do so in an unremarkable way that may go unnoticed, particularly by less experienced users. For this reason, developers expend substantial effort to include checks for inappropriate input parameters and accumulating errors. PWE codes have progressively become more robust over the past several years, and numerical problems are relatively rare except when a major new capability is first implemented.

HISTORY OF ELECTROMAGNETIC PWE MODELING IN THE U.S. NAVY

Electromagnetic propagation was described using PWEs as early as the 1940s by Fock,[24] but practical solutions were possible only for very simple atmospheric and surface boundary conditions. In 1973, however, Hardin and Tappert[25] introduced the FSS solution, which is a numerical method for directly solving the PWE using a Fourier transform, or "spectral," technique.[26] Ironically, Tappert first applied this method to EM propagation in the ionosphere, but circumstances soon caused him to focus on underwater propagation.[27] Although FSS PWE solutions rapidly became popular in the acoustic propagation community, they did not resurface (no pun intended) for EM problems until almost 10 years later.

As previously mentioned, an alternative numerical method for solving PWEs is to apply an IFD scheme that approximates the wave equation's partial derivatives with difference equations. This method was applied to EM wedge diffraction in 1968 by Popov.[28] The underwater community was using IFD PWE methods for larger scale propagation problems by 1981,[29,30] and through the years, the dialogue between proponents of IFD and FSS methods for acoustic propagation has been quite lively. IFD techniques have been, and still are, occasionally revisited for certain types of EM propagation applications.[31]

The FSS PWE model was introduced for tropospheric EM propagation by Ko et al.[32] in 1983; this model was called the Electromagnetic Parabolic Equation (EMPE) program and was based on an existing acoustic propagation code. EMPE initially allowed only perfectly conducting surfaces to be specified and had a number of other limitations. Subsequently, improved models were developed, including later versions of EMPE, which modeled more general surface boundaries and user-supplied antenna patterns. PWE models were also developed in other countries.[33,34]

EMPE was used with considerable success in post-test analyses and reconstructions of Navy tests beginning in 1984. These analyses used high-resolution, range-dependent refractivity information collected during test events, in conjunction with EMPE and radar system models, to explain observed system performance. This procedure permitted for the first time a quantitative analysis, including refractive effects, that relates measured performance to specified performance. Performance specifications typically assume standard, 4/3-Earth refractive conditions, and observed performance can be substantially enhanced or degraded relative to these specifications by nonstandard refractive conditions such as subrefraction, superrefraction, and ducting. The reader is referred to Ko et al.[32] for a discussion of standard and nonstandard refractive conditions.

By the late 1980s, dozens of Navy tests had been analyzed using EMPE, and the considerable success of those analyses caused U.S. Navy sponsors, most notably the Aegis Shipbuilding Program, to encourage the development of a PWE-based propagation model by SSC-SD, which is the U.S. Navy's designated laboratory for propagation model development. SSC-SD undertook this task and developed a PWE code called RPE (Radio Parabolic Equation),[35] which was later replaced by a "hybrid" PWE–geometric optics model, RPO (Radio Physical Optics).[36] A PWE model called PC Parabolic Equation Model (PCPEM) was also developed by RAL in the United Kingdom in this time frame.

RPO is a blend of PWE, geometric optics, flat-Earth, and PWE-initialized geometric optics models, with the choice of model depending on position, refractive condition, and other parameters. RPO was designed with speed as well as accuracy goals to satisfy the Navy's requirement for a shipboard propagation model to support rapid at-sea propagation assessments. As a result, some compromises in fidelity were made to allow for rapid computation. RPO development has been supported at various stages by the Office of Naval Technology (now combined with the Office of Naval Research), the Office of Naval Research, and the Naval Oceanographer's Office. RPO has gone on to become the "Navy standard" propagation model for operational applications involving over-water paths and surface-based systems. Interpretation of this "Navy certification" is discussed later in this article.

EMPE, which was developed by APL, was licensed to be sold commercially in 1987 by the original developers. In 1988, a research and development version of EMPE was renamed TEMPER (Tropospheric Electromagnetic Parabolic Equation Routine) to distinguish it from the commercial code. TEMPER is the program that continues to be APL's advanced propagation code in support of Navy projects. In 1989, the mixed Fourier transform (MFT) was developed for the PWE split-step solution and implemented in TEMPER.[4] This new solution rigorously incorporated an impedance boundary into the transform, permitting HF surface-wave calculations and accurate implementation of rough-surface impedance algorithms. Further improvements to the MFT decreased computation time and increased numerical stability.[5]

The need to represent propagation over land as well as sea was well established by the late 1980s in connection with littoral naval missions. Initially, the primary situation of interest for the surface Navy involved propagation from a shipboard system toward and over coastal terrain. More recently, Navy interest has expanded to include over-land propagation from higher altitude systems, such as surveillance aircraft. Propagation over land presents the challenge of specifying a lower boundary for the PWE that varies in height, roughness, conductivity, and permittivity with range. Several approaches to this problem have been investigated by APL, SSC-SD, NPS, and RAL (e.g., Refs. 6–8, 37, and 38).

In response to the need just described, SSC-SD developed the Terrain Parabolic Equation Model (TPEM),[6] the terrain mapping portion of which is based on work by Beilis and Tappert.[23] APL has been investigating the rigorous incorporation of the surface impedance and wide-angle propagation capabilities into this type of terrain-mapping algorithm (referred to hereafter as linear shift mapping),[39] while also experimenting with the other approaches described in Donohue and Kuttler.[37] TEMPER currently has two alternative methods for representing terrain: (1) the impedance-modified linear shift mapping just mentioned, and (2) a knife-edge method that simply inserts a perfectly conducting knife-edge at each range with height equal to the terrain height at that range. These two methods give similar results in "shadowed" regions where diffraction dominates but have different surface reflection characteristics. Comparisons between different terrain algorithms, including the TEMPER knife-edge and TPEM Beilis–Tappert methods, were performed for the 1995 EM Propagation Workshop.[20] These comparisons also included the hybridized TPEM (TERPEM) developed by RAL (see Fig. 1).

SSC-SD is currently working on a hybrid PWE model called APM (Advanced Propagation Model), which combines the capabilities of RPO and TPEM in a relatively fast code. As with RPO, minor compromises in accuracy are made in the interest of speed. APM uses hybrid techniques, similar to those in RPO, for propagation over land as well as sea, as long as the specified antenna height is below 100 m. For higher antennas, APM reverts to a full PWE mode. The expectation is that APM will replace both RPO and TPEM in the Navy's Oceanographic and Atmospheric Master Library (OAML).

Although there has been a very good interchange of ideas throughout the community of laboratories working on propagation, an especially useful relationship has developed between SSC-SD and APL. With the encouragement of the Aegis Shipbuilding Program, APL has delivered advanced algorithms, such as the previously mentioned MFT, to SSC-SD for evaluation and potential incorporation in their operational and R&D models. The MFT is now resident in TPEM and the APM prototype. The two organizations have also exchanged model source codes for mutual evaluation and testing. These collaborative efforts have resulted in rapid advancement of Navy propagation models. Figure 2 summarizes the chronology of, and relationships between, the various models discussed so far.

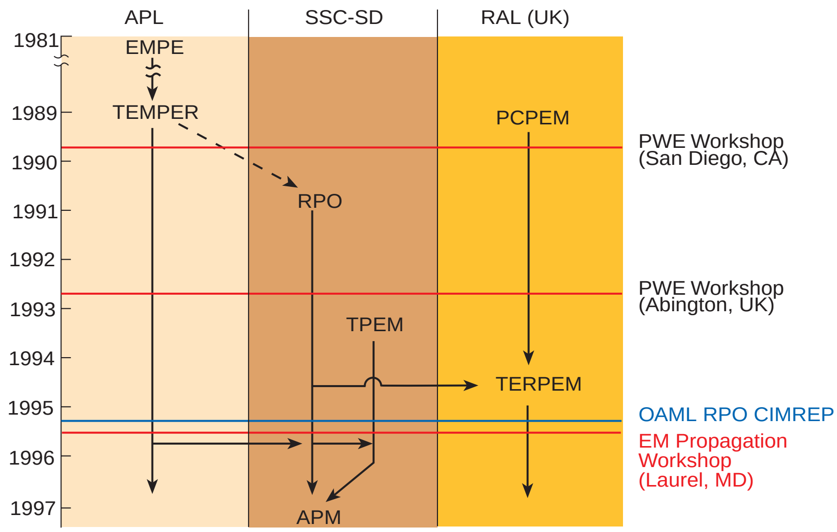

Figure 2. U.S. Navy electromagnetic parabolic wave equation model history. (EMPE = Electromagnetic Parabolic Equation, TEMPER = Tropospheric Electromagnetic Parabolic Equation Routine, SSC-SD = SPAWAR Systems Center San Diego, RAL = Rutherford Appleton Laboratories, RPO = Radio Physical Optics, PCPEM = PC Parabolic Equation Model, TPEM = Terrain Parabolic Equation Model, APM = Advanced Propagation Model, TERPEM = hybridized TPEM developed by RAL, PWE = parabolic wave equation, OAML = Oceanographic and Atmospheric Master Library, CIMREP = CNMOC Independent Model Review Panel, CNMOC = Commander of the Naval Meteorological and Oceanographic Command, EM = electromagnetic.)

CLASSES OF APPLICATIONS FOR PROPAGATION MODELS

As stated in the previous discussion, several PWE-based propagation models currently exist in the Navy engineering community, including RPO, TPEM, APM, and TEMPER in various versions. These models exhibit different strengths and weaknesses that are to some extent a function of their intended applications. To better match models to needs, the following five categories are identified:

1. Operational Assessment: This type of application includes propagation models embedded in tactical decision aids, mission planners, and performance assessment tools. In such applications, propagation models are typically required to execute rapidly over large domains and for the full range of parameters (frequency, polarization, antenna height, and beamwidth, etc.) associated with U.S. Navy sensor and communications systems. Furthermore, these models must be very robust in the sense that operation by inexperienced users will not result in errors or other numerical problems. The limitations on execution time and memory associated with shipboard use often force some compromises in model capability and/or accuracy.

2. Engineering Design: Propagation models are used to realistically simulate nominal and stressing natural environments in which to test new system designs. These simulated environments may influence selection of frequency, polarization, antenna pattern characteristics, operating bandwidth, and power margin. In this application, execution speed is usually less of an issue, but fidelity and capability requirements can be quite severe. The features of the propagation model may be tailored to emphasize fidelity in a particular risk area, such as antenna sidelobe control, monopulse operation, or surface scattering. Thus, models may be frequently modified to address particular features of the system under design, and to interface with detailed system simulations developed as part of the design process. In these situations, configuration control becomes difficult. In addition to being a design tool, propagation models are also used by government teams to evaluate contractor proposals and designs. The model requirements for this use are essentially the same as those just mentioned.

3. Test Performance Evaluation: Use of propagation models in post-test reconstruction and analysis has become relatively common, particularly for low-elevation tests where refraction, diffraction, and multipath are very important effects. For this application, the model must be able to accurately incorporate measured environmental data, including complicated range-varying refractivity, sea-state, and terrain characteristics. Although accuracy is important, uncertainties and variabilities in nature, as well as limitations in environmental data collection, will typically result in

uncertainties of several dB in propagation predictions. For this reason, capabilities such as surface roughness and terrain are the stressing requirements for propagation models, rather than speed and absolute accuracy.

4. Acquisition: There is a move afoot in the U.S. Navy to rely more on modeling and simulation, and less on actual field testing, for acceptance tests and demonstration tests of new or upgraded systems. In this role, a propagation model may end up embedded in, or providing data to, an advanced distributed simulation (ADS). How this connection to an ADS is approached has a large effect on the execution speed and interface requirements for the model. As a "run-time" participant in an ADS, execution speed would be critical, but as discussed earlier, the use of PWE models in time-step simulations is not usually practical. More likely, many propagation calculations would be performed in advance, and tables of the resulting data would be made available to the ADS members. In this case, speed is somewhat less of an issue (although a great number of off-line runs might be required to construct the tables), but accuracy remains very important. An error of a few dB may determine whether or not a system is accepted by the Navy.

5. Research: Many organizations use research-oriented PWE models to investigate particular aspects of EM propagation and to examine methods for improving computational speed and numerical accuracy. Some examples of less understood propagation effects currently under study are multiple surface scattering, terrain cover (grass, trees, etc.), surface-wave contributions, and three-dimensional scattering. Computational areas under investigation include "transparent" boundary conditions, nonlocal surface boundary conditions, and hybrid techniques involving mixtures of PWE, normal mode, geometric optics, and analytic methods. Models used for research purposes tend to be very accurate, but not necessarily fast or user-friendly. They are also continuously evolving, making them poor candidates for configuration control. Advances in propagation modeling resulting from these studies are eventually incorporated in more "production-like" codes.

Although some PWE models can serve in more than one of these applications, it should be clear that no single model will be suitable for all of them. The requirements for the different applications are diverse, particularly with regard to speed and accuracy. A matrix of desirable characteristics versus application type is shown in Table 1.

MODEL VERIFICATION, VALIDATION, AND CERTIFICATION

For certain of the applications just discussed, the U.S. Navy has an understandable desire to use only models that have been suitably validated and certified. Unfortunately, these terms have come to have different meanings to different organizations, resulting in confusion and the misapplication of some propagation models. It is important to realize that certification of a model is inevitably relative to some specified range of applications.

For the purposes of this discussion, "verified" means that the model has been demonstrated to execute its functions correctly, without consideration of whether or not its algorithms provide the required accuracy or capabilities. "Validation" means that, within its stated limitations, the model is providing accurate results; i.e., it is generating the correct answers. Finally, "certification" means that the model has gone through some formal approval process, and evidence of verification and validation are usually partial requirements for this approval. "Independent verification and validation" (IVV) refers to having verification/validation performed by an independent party, typically for the purpose of providing unbiased evidence of verification and validation to a certifying committee. The phrase "verification, validation, and accreditation" (VV&A) is also commonly used to refer to IVV plus certification.

Certification

Currently, the best-known certification process for Navy propagation models is acceptance into the OAML, which is maintained by the Commander of the Naval Meteorological and Oceanographic Command (CNMOC).[40] OAML's objective has been to maintain a library of certified models and databases for use by the

Table 1. Matrix of propagation model attributes and applications (H = high, M = medium, and L = low importance).

Application	Accuracy	Computation speed	Flexibility	Configuration control	Robustness	User interface
Operational assessment	M	H	L	H	H	H
Engineering design	H	M	H	M	M	M
Test performance evaluation	M	L	L	M	M	M
Acquisition/procurement	H	H	L	H	H	M
Research	H	L	H	L	L	L

operational U.S. Navy. Examples of operational uses include the Tactical Environmental Support System (TESS) and Geophysics Fleet Mission Program Library (GFMPL), both of which are presently deployed in the fleet. The models and databases in TESS and GFMPL reside in OAML. The RPO model is OAML certified, and the next-generation model, APM, was recently submitted as well. RPO underwent OAML certification because it was intended for use in a planned upgrade to TESS.

In contrast to operational uses, the engineering and R&D applications involve the use of models that are *not* currently being certified by OAML. Acceptance into OAML, which results in a certain degree of configuration control, would be problematic for such models because they are frequently being modified for specific, detailed applications, as well as being improved on the basis of research and testing. On the other hand, there is an important need for configuration control in operational applications, where the users are less likely to understand the differences between various models.

Although the OAML certification process includes IVV,[40] IVV has yet to be performed for an OAML EM propagation model. For example, in lieu of IVV, the RPO model was evaluated by a CNMOC Independent Model Review Panel (CIMREP) composed of propagation experts, most of whom were familiar with RPO. This panel documented the strengths and weaknesses of RPO and recommended that the model be accepted into OAML without awaiting IVV.[41] Thus, for practical reasons, OAML certification does not necessarily imply that IVV has been conducted for that model. Furthermore, OAML certification would not generally benefit engineering or R&D models. Presently, the primary functions of OAML regarding EM models are (1) configuration control of distributed operational models, (2) documentation of capabilities and limitations, and (3) distribution of models to requesting organizations.

In addition to OAML, there are a few other efforts to standardize and/or certify models for Navy use. The Aegis Program Executive Office (PEO SC/AP) has a model certification office (PMS-400B30M), which maintains the Aegis Simulation/Simulator Catalog.[42] In the Aegis process, “authentication” represents PEO SC/AP acknowledgment of the legitimacy of a model for Aegis applications and results in its inclusion in the catalog. Validation is an additional step tailored to the application planned for the model and is handled on a case-by-case basis. TEMPER is included in the Aegis catalog but has yet to go through the validation stage.

The Program Executive Office for Theater Air Defense, PEO(TAD), also contains a modeling and simulation office, PEO(TAD)MS, one of the goals of which is to identify and certify models appropriate for use in an ADS. PEO(TAD)MS attempts to be consistent with the Department of Defense Modeling and Simulation Office (DMSO). Specific procedures for PEO(TAD)MS certification have yet to be established but will almost certainly include compliance with the ADS high-level architecture (HLA) and should also involve validation and accreditation. For PWE models, the former objective may simply require the development of HLA-compliant “servers” to provide precalculated propagation data to the ADS.

So, what is the status of propagation model certification in the Navy? OAML certification means documentation and distribution of operational models. Aegis certification means ensuring that a model is appropriate for Aegis applications, with validation being an additional, unspecified procedure. PEO(TAD)MS certification will most likely emphasize architectural suitability for use in an ADS, although VV&A will also be addressed. None of the above “certifications” guarantee the suitability or accuracy of a propagation model for the applications described in the previous section. For this reason, the certification status of a model is often of little help in determining its suitability. It is generally more useful to consider the features, capabilities, and validation status of candidate models.

VALIDATION

Within the Navy community, PWE models have undergone extensive, but informal, verification and validation testing as they were developed. The most common type of test involves numerous comparisons with more rigorous, less flexible models, like normal-mode codes, as well as other PWE codes. The SSC-SD normal-mode model, MLAYER, has become the de facto benchmark program in the U.S. Navy EM propagation community.[4,22] In regions where propagation can be described by a limited number of modes (i.e., near and beyond the radio horizon), MLAYER gives excellent results for horizontally homogeneous refractive environments.[43]

TEMPER, RPO, TPEM, and other models were frequently compared at various stages during their development. Although such comparisons have been made informally and continuously over the past several years, the most fruitful activity occurred at the previously mentioned PWE Workshops and the EM Propagation Workshop.[20] Figure 1 shows an example of the comparisons conducted during the EM Propagation Workshop; the case shown is for propagation over a mixed land–sea path as calculated by TEMPER and RAL’s TERPEM. The quantity plotted in Fig. 1 is propagation factor, which is nominally defined as the radiated power normalized relative to what it would be in free space. A color-modulated “coverage” plot and a vertical cut through this plot at 100 km are presented. The color contour plot illustrates effects due to multipath, refraction due to the 400-m surface duct, and diffraction behind the terrain obstacles. In this example, the agreement between TEMPER and TERPEM is seen to be excellent. Comparisons of this type have ultimately exhibited the accuracy and limitations of the participating models, and essentially formed the basis for the CIMREP recommendation to accept RPO into OAML. Also as a result of these comparisons, TEMPER has emerged as a high-fidelity reference standard for U.S. Navy PWE models.

Comparisons with measured data have been conducted by the respective developing organizations for some models. Extensive experimental campaigns were executed in the late 1980s to validate TEMPER,[12] and more recently, RPO and TPEM have been shown to compare favorably with measured data.[6,13,20] These comparisons, in conjunction with successful reconstruction of low-altitude radar system performance during Navy tests, have established high confidence in PWE-based propagation models.

CONSIDERATIONS FOR SELECTING EM PROPAGATION MODELS

In this author's opinion, selection of an EM propagation model for a particular application should be based on each candidate model's demonstrated accuracy, robustness, computational speed, and features. Unfortunately, there does not presently exist a centralized or certified record of these attributes, and the burden of making an informed choice falls to the potential user. One could argue with some justification that RPO is the only "certified" U.S. Navy PWE model, but RPO's features support only over-water, low-antenna-height applications, and the model's accuracy has been certified only for operational, rather than engineering or research, uses.

Without addressing details regarding specific applications, some general guidelines can be recommended on model application. In the following paragraphs, such guidelines are suggested for models that have been developed under U.S. Navy sponsorship. Although these guidelines were generated by the author, they reflect numerous interchanges with the respective model developers and are believed to be noncontroversial. Table 2 summarizes qualitatively the attributes and applications of each code.

TEMPER is currently the highest fidelity U.S. Navy EM PWE model and is used as a baseline for less rigorous models. TEMPER is also used in high-fidelity engineering design and post-test reconstruction tasks, as well as to investigate new rough-surface algorithms and HF surface-wave propagation. This model has the fewest restrictions on antenna height, antenna patterns, surface characteristics, and steep-angle propagation, although very large computation times can result for large problem domains. The TEMPER algorithms that have been shown to provide new or improved capabilities to PWE models are passed on to SSC-SD for incorporation in their propagation codes.

Table 2. Attributes and recommended applications for Navy parabolic wave equation propagation models.

Model	Type	Attributes	Applications	Certification
RPO	Hybrid GO/PWE	Fast Moderate accuracy Over-water only Low antennas only	Operational assessment Engineering studies	OAML
TPEM	PWE	Medium Good accuracy Terrain capability	Engineering studies High-level design studies	Submitted to OAML
APM	Hybrid GO/PWE	Fast Good accuracy Terrain capability	Operational assessment Engineering studies High-level design studies Post-test analysis	Soon to be submitted to OAML
TEMPER	PWE	Medium to slow Excellent accuracy Terrain capability	Detailed design studies Detailed performance simulations Post-test analysis Propagation R&D	Aegis Simulation/ Simulator Catalog

Note: RPO = Radio Physical Optics, GO = Geometric Optics, PWE = parabolic wave equation, OAML = Oceanographic and Atmospheric Master Library, TPEM = Terrain Parabolic Equation Model, APM = Advanced Propagation Model, TEMPER = Tropospheric Electromagnetic Parabolic Equation Routine.

RPO is suitable for over-water, surface-based system calculations, when it is acceptable to sacrifice a little accuracy in return for reduced execution times. This description suggests its use for over-water calculations in shipboard environmental assessment programs, such as TESS, where the uncertainties in atmospheric data are considerable and computation speed is important. RPO may be used for some types of engineering studies provided polarization, surface roughness, and near-surface field effects are not important to the study. RPO also has some limitations on antenna pattern representation; these limitations are adequately discussed in the OAML documentation.

TPEM is a full-PWE model emphasizing over-land propagation and will often have similar execution times to TEMPER. The steepness (relative to the local horizontal) of energy scattered from terrain features is limited in return for containing execution time to some degree. Also in the interest of simplicity, there are limitations to the land characteristics that can be specified. TPEM can be used in moderately high-fidelity engineering applications where fine-scale roughness on land and high-angle scattering from land are not important (as is often the case).

The forthcoming APM model will combine RPO and TPEM with a considerable number of improvements to both. For sufficiently low antenna heights, both over-sea and over-land calculations will be hybrid, as they are in RPO for over-sea, and improved polarization and roughness models will be incorporated into the over-water portion as well. APM attempts to maintain the rapid execution times realized with RPO while retaining fidelity up to at least TPEM's level. Antenna heights larger than 100 m will cause APM to revert to a full-PWE mode. Although future testing is needed to establish the level of accuracy obtained by APM, it will certainly be suited to operational applications and will likely be appropriate for some engineering tasks as well.

SUMMARY

With the development of PWE-based models during the past 15 years, the Navy now has very capable tools for analyzing and predicting EM propagation effects. Calculations over land and sea, with varying electrical and roughness characteristics and a wide range of system parameters, are now feasible, and users have the flexibility of trading off computational speed, accuracy, and other attributes by choosing from the available models. Although the various models have been developed with different objectives and intended applications, many comparisons between them, both formal and informal, have been performed. Furthermore, each developing organization has expended substantial effort internally to validate its code's performance. Finally, and perhaps most importantly, these models have been widely used, with excellent success, in many Navy programs.

On the other hand, systematic categorization, validation, and formal accreditation have yet to be accomplished. These steps are increasingly important as the Navy and other services place more and more emphasis on modeling and simulation. The guiding principle in validation and certification/accreditation should be to conduct these activities in the context of intended applications and requirements. In this way, the danger of selecting an inappropriate model for a particular task will be greatly reduced.

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