EM Propagation (METOC Impacts)

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LONG TERM GOALS

Develop electromagnetic propagation models, that perform equally well over land and sea and in the presence of anomalous propagation conditions for both surface and airborne emitters, for use in operational or engineering propagation assessment systems.

OBJECTIVES

Develop an advanced unified hybrid radio propagation model based on parabolic equation and ray-optics methods for both surface-based and airborne applications. This model is named the Advanced Propagation Model (APM) and is the model used in the Advanced Refractive Effects Prediction System (AREPS). Other objectives are to develop a propagation model for earth-satellite geometries suitable for inclusion into the Advanced Propagation Model (APM) or alternately, suitable for transition to the Advanced Refractive Effects Prediction System (AREPS) and the Naval Integrated Tactical Environmental Subsystem (NITES) II Redesign (N2R). As part of this development effort, an enhanced absorption model will be updated and rain attenuation models will be included within APM and the Earth-to-Space Propagation (with Meteorology) Module ($ESPM^2$). We will also perform a sensitivity study of the turbulent structure parameter using the Rough Evaporation Duct (RED) measurements. As a result of this study we will develop a suitable algorithm within APM accounting for turbulent effects in the marine boundary layer, providing a variance of the predicted instantaneous field strength.

APPROACH

We develop parabolic equation (PE), ray optics, waveguide, and other models as necessary to produce both accurate and efficient models to be used in propagation assessment systems. In many cases we can use variations of existing models to achieve this goal, but sometimes completely new models are

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14. ABSTRACT
Develop electromagnetic propagation models, that perform equally well over land and sea and in the presence of anomalous propagation conditions for both surface and airborne emitters, for use in operational or engineering propagation assessment systems.

15. SUBJECT TERMS

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necessary. Once developed, these models are compared to other models and to experimentally collected propagation data for verification of accuracy. We stay abreast of other researchers' newest models by reading current literature, participating in propagation workshops, and attending conferences as appropriate. We continually examine new modeling techniques that may offer improvements in prediction accuracy or execution time. There is a strong international exchange of ideas and techniques in this area, as some important work is performed outside of the USA. This ongoing project has resulted in a hybrid ray optics/parabolic equation propagation model for assessing the effects of the atmosphere and the environment in general on electromagnetic emissions in the range of 2 MHz to 57 GHz for both surface based and airborne transmitters.

The vertically varying profile computed from bulk models is considered to represent the refractive mean and is the only atmospheric input normally considered in predicting field strength over water. The result is that the prediction also represents a *mean* instantaneous field strength, and in reality the field will fluctuate about this mean by some variance that is a function of the turbulent structure parameter. The bulk measurement data set that we will use to obtain vertical refractivity, as well as structure parameter profiles, will be that taken during the Rough Evaporation Duct measurement campaign [1]. We will use the computed structure parameter to perform a sensitivity study using APM to determine the variations in the field strength due to this parameter. The technique used within the APM to do this will be based on a modification to the method developed by Hitney, which considered applying fluctuations in the refractive index due to the turbulent structure parameter to model tropospheric scatter [2].

This project is divided into two tasks: (1) Metoc Impacts and EM Performance Assessment for Earth-Space Geometries, PI Dr. Richard Sprague; and (2) Atmospheric Surface Layer Turbulence Effects on Microwave Signal Level, PI Amalia Barrios.

WORK COMPLETED

METOC IMPACTS AND EM PERFORMANCE ASSESSMENT FOR EARTH-SPACE GEOMETRIES

The ray tracing program developed in the previous year was further enhanced by the development of a range dependent atmospheric refractivity capability. With this new capability, the user has the ability to enter an arbitrary number of refractive height profiles, each specifying the height dependent refractivity within a sub-section of the propagation path. This provides an important predictive improvement to the model, especially for low elevation satellites and ducting refractive conditions; scenarios for which the model is specifically targeted. We have also implemented a satellite orbit prediction capability which provides an accurate estimate of the location of a specified satellite at a given time. This is a critical input to the ray trace program, especially for the target scenarios. Finally, the range dependent model and the orbit determination program are currently being converted from MATLAB to FORTRAN and unified into a single program suitable for future implementation in AREPS.

ATMOSPHERIC SURFACE LAYER TURBULENCE EFFECTS ON MICROWAVE SIGNAL LEVEL

The PE algorithm within APM was modified to incorporate a random realization of the fast-fluctuating turbulent portion of refractive index based on the 3-dimensional Kolmogorov spectrum, which is a function of the turbulence wavenumber, κ, and C_n^2 [3]. The turbulence wavenumber is a function of the scale length, L_s, which in this implementation is computed as a function of height and range based on classical theory and the formula for the outer scale length, L_o. Classical theory states that $l_o < \sqrt{\lambda L} < L_o$, where l_o is the inner scale length and L is the propagation path length [4]. The outer scale length within the surface layer is also generally given by $L_o = 0.4z$ (assuming a neutral atmosphere), where z is the height above the surface. For the entire range of values for l_o (typically on the order of 1 mm to 1 cm) the left-hand side of the relationship is easily satisfied for most practical cases of interest. However, L_o, varies from 10 m to 100 m and therefore, the right-hand side of the relationship must be more carefully tracked. In the context of the PE algorithm the PE range step, r_{PE}, is equivalent to the path length L as the field is "marched in range". Therefore, for any particular range, κ will vary with height according to 0.4z but will also be "bandlimited" by $\sqrt{\lambda r_{PE}}$. With κ determined as described, the random realization of the turbulent portion of the refractive index, n_s, is given by

$$n_s = \frac{r - 0.5}{.289}\sqrt{0.033 C_n^2 \kappa^{-11/3}},$$
$$\kappa = 2\pi / L_s \, ; \; L_s = \min\left(0.4z, \sqrt{\lambda r_{PE}}\right),$$

where r is a uniformly distributed random number from 0 to 1. This fluctuating term, described by the 3-dimensional Kolmogorov spectrum is then added to the mean refractive index profile within the PE algorithm.

The APM was then run 256 times (i.e., 256 random realizations) for each 5 minute period to simulate the data collection procedure. The mean and standard deviation of the predicted loss values were then computed and analyzed against observations to determine the validity of the current implementation to model turbulent effects.

This task is still ongoing and will be completed by the end of CY07. Current results are discussed in the next section.

RESULTS

METOC IMPACTS AND EM PERFORMANCE ASSESSMENT FOR EARTH-SPACE GEOMETRIES

Although APM contains a ray-trace capability, it employs small angle approximations which make it suitable only for terrestrial paths. For earth-satellite (ES) geometries, large ray angles (relative to the horizontal) are the rule and so a more general ray-tracing capability had to be developed. However, while large ray angles are the rule, the most critical scenario for the use of this assessment tool is envisioned to be communication to satellites low on the transmitter's horizon, i.e., at small angles. This is especially true in extreme ducting conditions when ray trapping may exclude any communication between the satellite and a ground station. Under these conditions the signal loss can also become very large, making communication impossible even if a signal path can be established.

In last years report we included a figure showing ray trapping in a refractive duct. For the range independent ray trace program it is not possible to predict those well-documented instances where anomalous propagation to large beyond-line-of-sight ranges is observed. Usually, such cases require that the electromagnetic energy, propagated to large distances within the duct, escape to be detected at measuring locations outside the duct, for example, at satellite heights. These cases require some refractive inhomogeneity along the horizontal direction to allow the energy to escape the duct. An example is shown in Fig. 1 below where the escape of energy is shown for range dependent refractivity.

In Fig. 1, the left hand panel shows the refractive height profiles for this two sub-region (sector) propagation path. In sector 1 a strong ducting condition exists which effectively traps rays launched near 90° zenith angle. This is shown in the top panel on the right side in the figure where the duct is assumed to exist along the entire path. If the non-ducting profile is specified in sector 2, at a fixed ground range from the transmitter, the rays escape and can then continue on to reach satellite heights where they may provide communication capability. This is shown in the bottom panel on the right side of the figure. This indicates the importance of a range dependent capability for certain scenarios. Details of the ray trace method are described in a SPAWAR Technical document to be published [5].

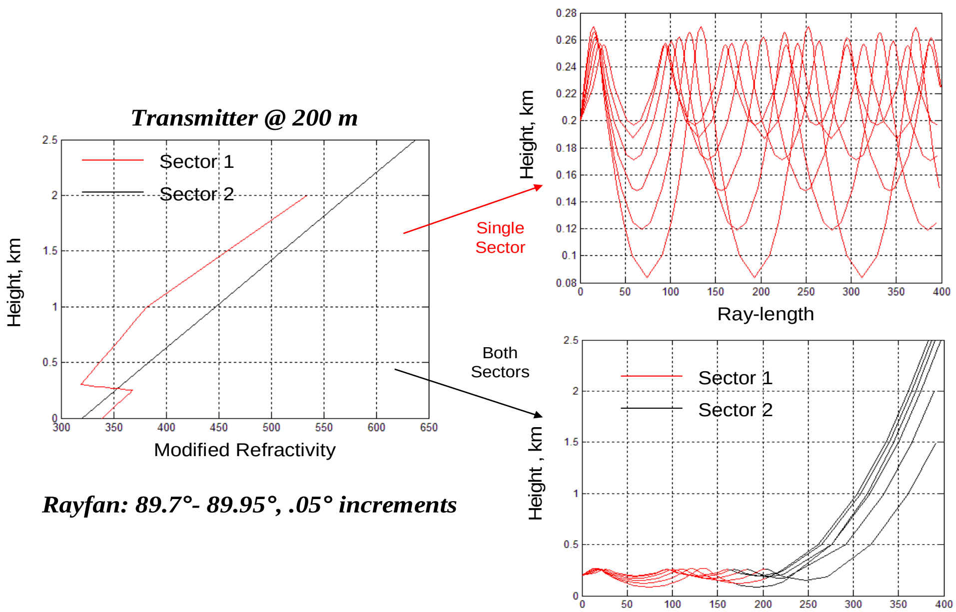


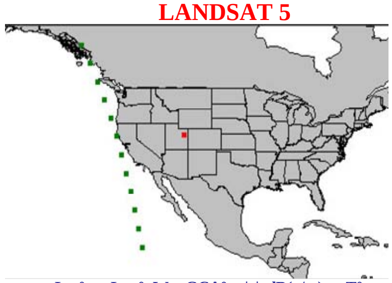
Figure 1. Illustration of the importance of range dependent refractivity for ducting conditions in satellite communications. Initially trapped rays may propagate to satellite heights by escaping the duct.

Another important enhancement to the model which we have implemented this year is the ability for the user to specify the satellite location using orbital prediction software. We have included two orbital prediction models, designated SGP4 and SDP4, developed for the North American Aerospace Defense Command (NORAD), which is a ‘bi-national United States and Canadian organization charged with the missions of aerospace warning and aerospace control for North America. Aerospace warning includes the monitoring of man-made objects in space, and the detection, validation, and warning of attack against North America whether by aircraft, missiles, or space vehicles, through mutual support arrangements with other commands. Aerospace control includes ensuring air sovereignty and air defense of the airspace of Canada and the United States’ (NORAD web site). To accomplish this mission, NORAD maintains and publishes the precise satellite location information necessary for the

calculation of satellite orbits for ‘all resident space objects’ [6]. This information is available on-line in the form of ‘two-line element sets’ (TLE) for each satellite. The TLE provides the input data for execution of the orbital prediction models.
The models SGP4, for near earth satellites (orbital period less than 255 minutes) and SDP4 for deep space orbiters, including geo-stationary satellites, require NORAD TLE orbital element files for execution. The driver program selects the appropriate model based on the input data, a process that is transparent to the user. The basic output from the program consists of the satellite location and velocity at the required time, in the inertial coordinate system used for the calculations. Documentation of the details of the programs SGP4 and SDP4 are available in [6].

While the orbital programs provide satellite location in an inertial frame used for the program calculations, we require the location in the earth centered system used in the ray trace program. As part of the effort this year, software for this conversion, as well as for determination of other necessary parameters was developed and implemented. The following figure shows a typical scenario in which a user might employ the orbital program and the ray trace software to provide system performance predictions.

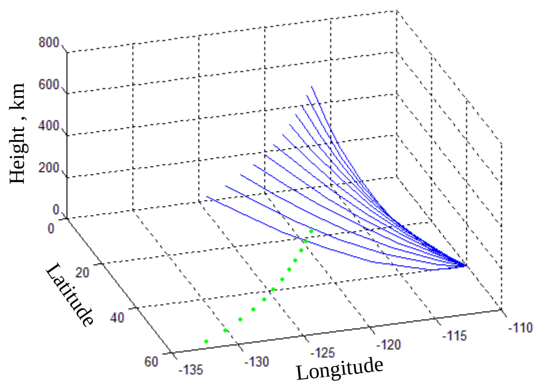
LANDSAT 5



Lat°	Lon°, W	GCA°	|e|, dB(v/m)	T°
57.45	131.97	22.47	-125.29	86.44
53.92	130.08	19.40	-119.96	82.76
50.37	128.44	16.55	-116.86	78.64
46.80	127.00	14.06	-114.60	74.24
43.23	125.71	12.16	-112.96	70.15
39.64	124.53	11.15	-112.09	67.63
36.05	123.44	11.29	-112.21	67.97
32.46	122.43	12.53	-113.27	70.96
28.86	121.48	14.59	-115.06	75.21
25.26	120.57	17.19	-117.48	79.58
21.65	119.70	20.12	-120.88	83.62
18.05	118.86	23.25	-127.34	87.19

One Minute Orbital Samples

Transmitter @ 40 N, 110 W



GCA°= Great-Circle Angle in degrees
T°= Pointing Angle at Transmitter in degrees from zenith
dB(V/m)= deci-Bels relative to 1 v/m for 1 W transmitted

Figure 2. Illustration of the use of the orbital software together with the ray trace program to provide estimates of signal parameters at the satellite.

In Fig. 2, the orbital program was used to predict satellite locations for a given time period in one of its orbits. The TLE was downloaded from a web site which provides these data for almost all satellites. Given the satellite locations, it was determined that the satellite would rise above the local horizon of the transmitter site for about 12 minutes during the orbit. We then used the ray trace program to determine the launch angle for the rays which connected the transmitter and satellite at one minute intervals during the time the satellite was visible to the transmitter. From the rays we estimated the expected signal strength at the satellite and antenna pointing angles for optimum communication.

ATMOSPHERIC SURFACE LAYER TURBULENCE EFFECTS ON MICROWAVE SIGNAL LEVEL

The frequencies at which radio data were collected during RED were 3 GHz, 9.7 GHz, and 17.7 GHz. The transmitting antennas were located at two heights above the surface at 4.9 m and 12.7 m, with the receiver height at 4.7 m. The radio propagation data was collected for each combination of 6 transmitter/frequency geometries for a period of 5 minutes each. The signal was sampled at a rate of 256 samples per 5 minute period and the mean of the propagation loss, along with the standard deviation for each 5 minute period was computed. The Naval Postgraduate School (NPS) bulk model [3], which computes the evaporation duct refractivity profile based on bulk measurements of air/sea temperature, wind speed, and humidity was modified to also compute the height-varying structure parameter, C_n^2.

Over each 5 minute sampling period, the radio propagation data varied from its average by a standard deviation value determined from the 256 samples during this period. This variation is attributable to turbulence and not noise due to the fact that the signal variance was not consistent across the three frequency bands used in the RED experiment. The standard deviation for much of the X-Band data and roughly all the S-Band data is 1 dB. The standard deviation for the Ku-Band propagation data, however, was distributed over a wider range of values from 1 to 6 dB for the entire two-week IOP, as shown in Fig. 3. Therefore, only the Ku-Band radio data was used in the analysis. One feature to note is the double-peak in the Ku-band standard deviation distribution for both the high and low antenna heights. The cause of the second peak, centered at roughly 5 dB, is currently unknown.

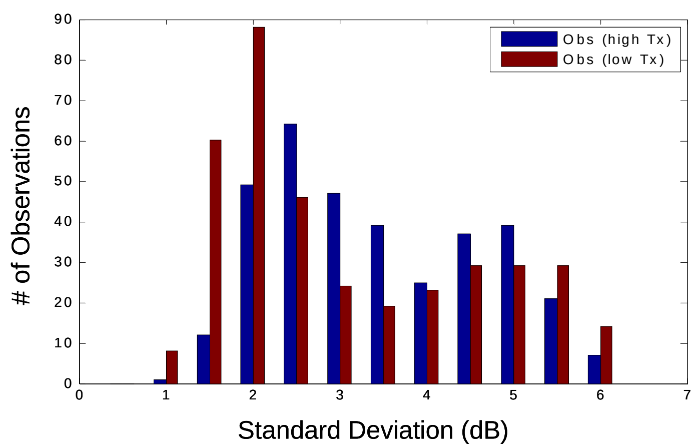


Figure 3. Standard deviation of radio data collected during RED at Ku-band for both the high antenna (blue) and low antenna (red).

An example coverage diagram showing modeled propagation loss with and without turbulence is provided in Fig. 4. The environment is a 13.1 m evaporation duct height, along with C_n^2 profile, computed from bulk parameters measured on day 246.316 UTC. The transmitter antenna height is 12.7 m. Fig. 4(b) shows the effects on the propagation loss from one random realization of the fluctuating portion of the refractive index.

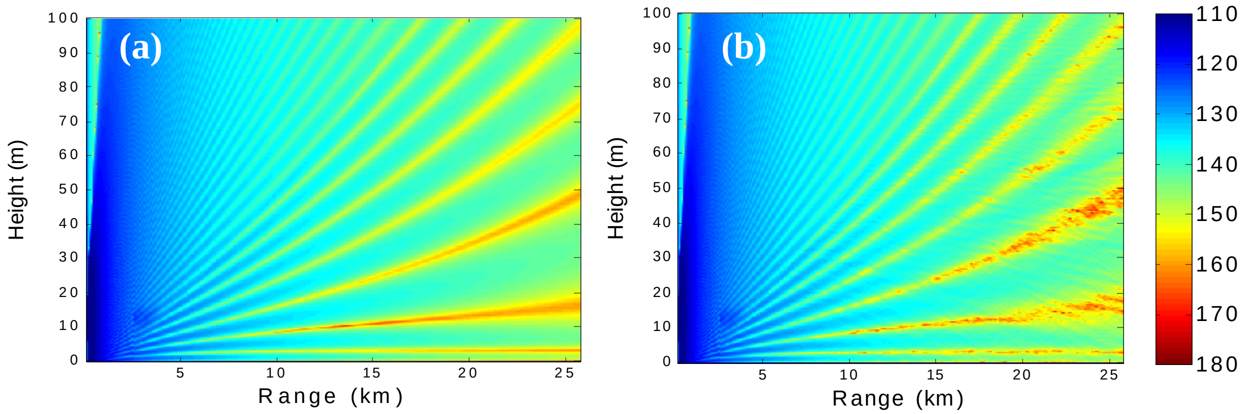


Figure 4. Modeled propagation loss (a) without turbulence, and (b) with turbulence for a 13.1 m evaporation duct, high transmitting antenna (12.7 m).

The standard deviation computed from 256 realizations of predicted propagation loss is shown against the observed standard deviation, for each 5 min. measurement period, in Fig. 5. The RMS error for the high antenna is 1.48 dB and for the low antenna is somewhat greater at 2.23 dB. Using the 1-dimensional form of the Kolmogorov spectrum, which has a power-law dependence of '-5/3', produced just slightly lower RMS error values of 1.39 dB for the high antenna and 2.14 dB for the low antenna. Work is continuing on this task through the end of CY07.

IMPACT/APPLICATIONS

The goal of this work is to produce operational radio propagation models for incorporation into U.S. Navy assessment systems. Current plans call for the APM to be the single model for all tropospheric radio propagation applications. As APM is developed it will be properly documented for delivery to OAML, from which it will be available for incorporation into Navy assessment systems. Recent optimizations and enhancements of APM not only benefits the U.S. Navy but also **unifies** the overall military EM performance assessment capability by having a single high-fidelity propagation model that performs equally well over land and sea and in the presence of anomalous propagation conditions.

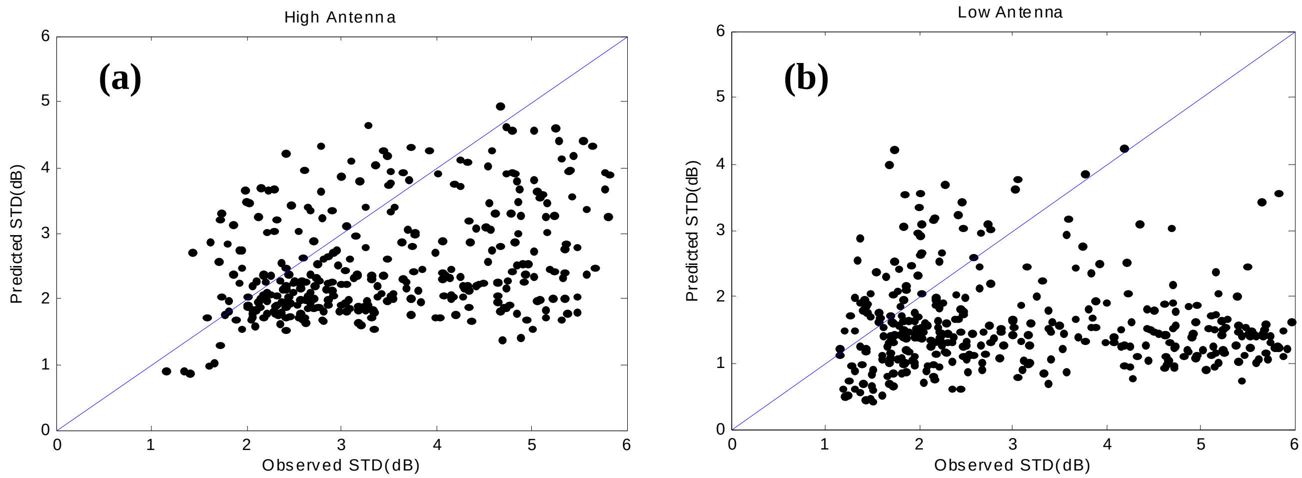


Figure 5. Predicted vs. observed standard deviation for (a) 12.7 m antenna (high), and (b) 4.9 m antenna (low).

The primary payoff of including the ability to model turbulence effects in APM is providing the U.S. Navy a radiowave propagation model providing instantaneous field strength along with a quantitative degree of confidence or uncertainty in the prediction. The ability to model turbulent effects at microwave and millimeter frequencies within the marine boundary layer is an important capability in a RF propagation model in order to provide some level of uncertainty, or confidence level, in assessing the performance of a radar against low-flying targets.

With the development of the ESPM[2], the Navy and Marine Corps, as well as Army communicators, will also have a propagation model for SATCOM performance assessment to allow optimization of communications.

TRANSITIONS

All APM modifications and added capabilities transition into the Tactical EM/EO Propagation Models Project (PE 0603207N) under PMW 180 which has produced the Advanced Refractive Effects Prediction System (AREPS). Academia and other U.S. government are also utilizing APM/AREPS. The APM is currently being used by foreign agencies as the underlying propagation model within their own assessment software packages. The APM has also been adopted as the preferred propagation model in the Ship Air Defence Model (SADM), which is an operational analysis software tool developed to simulate the defense of a naval task group against multiple attacking anti-ship missiles and aircraft. BAE Systems, Australia are the developers of SADM and some of their customers include U.S. DoD agencies.

RELATED PROJECTS

This project is closely related to the synoptic and mesoscale numerical analysis and prediction projects pursued by NRL Monterey.

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