Modeling RF Digital Signals for Communications Applications

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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 an earth-to-satellite propagation (with METOC) model, ESPM2, suitable for transition to the Advanced Refractive Effects Prediction System (AREPS) and the Naval Integrated Tactical Environmental Subsystem (NITES)-Next. The specific technical objectives are to modify the APM to model wideband sources for accurate characterization of the propagation channel for RF communications systems; and modify the ESPM2 to assess the impact on communication system performance of channel limitations imposed by propagation through the ionosphere.

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15. SUBJECT TERMS

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APPROACH

Although the APM provides a powerful tool for radar performance assessment, it does not provide the same capability for assessing the performance of modern communication systems. The current method of determining propagation loss for single frequency sources is insufficient for RF digital communications applications. Proper characterization of the transmission channel for frequency-hopper and other wideband waveforms is required for determining the quality of the communication link and can be achieved by modifying the APM. The model uses the split step parabolic equation (PE) algorithm to determine the complex field (amplitude and phase) of a CW source. The channel transfer function for a wideband channel is computed by dividing the bandwidth of interest into multiple frequency bins with appropriate spacing and computing the complex field at each bin. The impulse response is then computed by taking the inverse discrete Fourier transform of the transfer function, where the bandwidth used determines the time resolution of the impulse response and the frequency spacing determines its time window. In order to gain a further understanding of the model, the channel impulse response is computed for an ideal case having a direct and reflected path with a known solution, as well as for examples using a duct profile over water , standard atmosphere over terrain, and terrain along with a surface-based duct measured along the coast of southern California.

For computational efficiency fast Fourier transforms (FFTs) are used by the PE algorithm to transform from the spatial height domain, *z*, to the frequency domain, *p*. In doing so the height step, Δz, is determined by the Nyquist criteria as

$$\Delta z = \frac{c}{2 f \sin \theta_{\max}} ,$$

where θ_{max} denotes the PE angle selected each time the algorithm is run, *c* is the speed of light, and *f* is the source frequency [1]. The algorithm is run multiple times to compute the transfer function of the channel by obtaining the amplitude and phase of the frequencies selected over the bandwidth of interest. Each time the algorithm is run Δz is kept constant to ensure that the complex field is evaluated at the exact receiver height. By fixing Δz, as *f* increases, θ_{max} decreases. There are two considerations to keep in mind when selecting θ_{max}. First, θ_{max} needs to be large enough so that the field consists of every multipath arrival present at the receiver. Second θ_{max} must not be large enough to violate the assumptions made by the PE model.

Ray tracing is utilized to determine θ_{max} for a specific system geometry. By employing a simple geometric ray tracing tool, the number of multipath arrivals, the arrival times of each ray, as well as the elevation angles from the transmitter to which the rays are traced to the receiver can be determined. By computing the highest magnitude of the elevation angles, the minimum value of θ_{max} that is needed to run the PE algorithm across the frequency band is determined. The fact that for a given range the transfer function for multiple receiver height locations can be computed using the same number of PE runs is exploited. When computing the transfer function at multiple receiver heights, the minimum value of θ_{max} should take into account each ray traced to every receiver location. The minimum value of θ_{max} corresponds to the PE angle chosen for the stopping frequency in the bandwidth of interest. The value of the PE angle at the stopping frequency determines the PE angle at starting frequency, which must not be large enough to violate the assumptions made by the model. These angles limit the size of the bandwidth for which the channel can be modeled using this approach.

The ray tracing utility can only be used for cases in which terrain is not included. When terrain is present the PE angle needed to encompass all of the multipath arrivals should be kept large to ensure that all of the refractive effects are taken into account. The approach used to determine the PE angles for a given bandwidth is to calculate the angles to be as large as possible without violating the assumptions of the model.

For frequencies used in satellite communications, the refractive effect of free electrons in the ionosphere is usually ignored. However, the frequency dependence of phase velocity within the ionosphere causes a wave packet to 'spread' in time. This spreading, if severe enough, can produce inter-symbol interference in digital systems, which degrades system performance. This spreading is enhanced for satellites near the horizon due to the increased path length within the ionosphere. A model called 'NeQuick' was developed and made available by the ITU [2] for use in TEC calculations. The model is used extensively in the community and its accuracy has proved acceptable, relative to IRI and PIM [3,4]. It is the NeQuick model that is used in our study to include ionospheric effects in ESPM2.

WORK COMPLETED

Using the APM, the impulse response was determined for four cases. All cases are computed for an omni-directional antenna and for horizontal polarization. First, a simple case is considered for energy propagating over water in a standard environment. This case has a known solution for the arrival times of the direct and reflected rays, offering a way to verify the results. Next the impulse response computation is verified using ray tracing for energy propagating over water in an environment with a 300 m surface-based duct. In this environment there are multiple arrivals present depending on the geometry used. After verifying the impulse response computation, terrain is included. A simple wedge is used to evaluate the effects of terrain. Finally, the effects that can be present in a real environment are demonstrated using a real terrain profile and using radiosonde data taken off the coast of Southern California.

The portion of this effort for the enhancement of modeling capabilities within the ESPM2 was completed in FY08 and was reported in the ONR FY08 Annual report and in [5,6].

RESULTS

Impulse Response

For the standard environment, over water case, the impulse response is computed for a transmitter height of 150 m, a receiver range of 5 km, and three receiver heights at 50 m, 200 m, and 500 m. The impulse response was computed for a receiver height of 200 m in [7] from which the results can be compared. The result is also verified by noting that the arrival time of the direct ray at the 500 m receiver should be the same as the arrival time of the reflected ray at the 200 m receiver. The time difference between the direct and reflected arrivals is approximately 10 ns at the 50 m height, 40 ns at 200 m, and 100 ns at 500 m. The time difference between the first and last arrival to all of the receiver heights is approximately 140 ns. Based on these values a time step of 7.8 ns and an overall time window of 1μs have been chosen. These values set the bandwidth to 128 MHz and the frequency spacing to 1 MHz. The center frequency is chosen as 200 MHz. These parameters are chosen not for a specific system, but to attempt to resolve the multipath arrivals.

Figure 1A shows the results obtained after using an inverse discrete Fourier transform. The values shown in the parenthesis are the actual delay differences determined using ray tracing and the values outside the parentheses are the model estimates. Since the time step chosen is 7.8 ns, the estimated values are within the margin of error.

The next case is over water as well with a 300 m surface-based duct. The impulse response is computed for a transmitter height of 25 m, a receiver range of 200 km, and three receiver heights at 50 m, 200 m, and 500 m. From ray tracing, two arrivals are predicted at the 50 m receiver height. The time difference between these arrivals is 2 ns. There are three arrivals predicted at the 200 m receiver height. The predicted delay difference between the first and second arrivals is 3.7 ns and between the second and third is 8.3 ns. The receiver at the 500 m height is outside of the duct and no arrivals are predicted. The time difference between the first and last arrival of all of the receiver heights is approximately 12 ns. Based on these values, a time step of 1 ns and an overall time window of 128 ns have been chosen. These values set the bandwidth to 1000 MHz and the frequency spacing to 7.8 MHz. The center frequency is set to 1500 MHz.

Figure 1B shows the impulse responses obtained using the parameters described above. The time step is 1 ns and is not enough to resolve the two arrivals at the 50 m receiver height. The values of the actual differences and the estimates at 200 m are in agreement since the difference between the values is within 1 ns. The 500 m receiver result shows a weak arrival, which is expected.

The next example uses a wedge terrain and a standard environment. In the previous two cases, a geometric ray trace is used to determine the PE angle needed to account for all of the multipath arrivals. The determination of the bandwidth and the frequency spacing was based on the arrival times determined by the ray trace. This capability is not available when terrain is included. A higher PE angle will be needed to account for the interaction of the field with the terrain. The approach used to determine the PE angles is to keep them as high as possible over the bandwidth used without violating the assumptions made by the model. As a starting point, the geometric ray trace can determine the bandwidth and frequency spacing to use when excluding the terrain. These values are increased in order to define the same parameters when terrain is included.

The impulse response is computed for a transmitter height of 25 m, a receiver range of 60 km, and four receiver heights at 50 m, 200 m, 500 m, and 1001 m. The wedge extends from 40 km to 60 km in range and its peak is at 200 m. The bandwidth chosen is 1500 MHz and the frequency spacing is 5.9 MHz giving a time step of 0.67 ns and a time window of 171 ns. The center frequency is set to 1000 MHz.

Figure 1C shows the impulse responses at the four receiver heights. To understand these results, a comparison is done against results (not shown) obtained for the same geometry and environment, but taken instead over water. With terrain, the 50 m receiver does not have line of sight to the transmitter. The result is that the arrival at this receiver is delayed further, is weaker, and the pulse is wider than the arrival excluding terrain. The arrival at the 200 m receiver is also weaker than the over water case. At 500 m, the diffraction due to the wedge peak should cause a greater number of multipath arrivals than when terrain is excluded. The second peak shown in Figure 1C for this receiver is not present when terrain is excluded, so this extra arrival that has been resolved is due to the diffraction effects. The results are practically equivalent at the 1001 m receiver because the receiver is high enough that the wedge does not significantly affect the multipath returns.

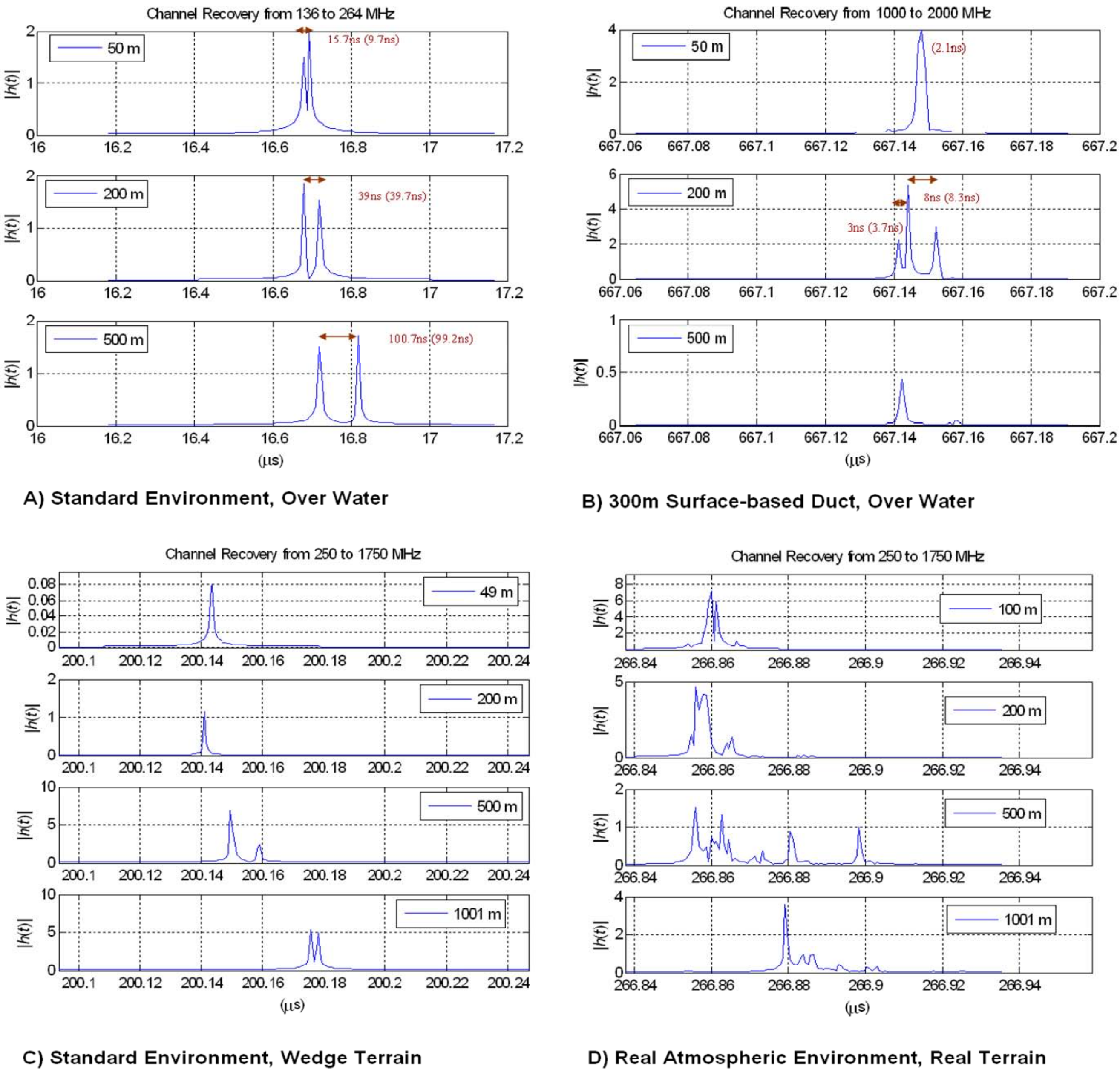

Figure 1. Impulse response showing the relative time delay difference between the field components.

Next, to demonstrate the effects that can be present in real atmospheric environments, a measured 400 m surface-based duct taken from a radiosonde off the coast of Southern California is used along with a real terrain profile. The transmitter height is 25 m, the receiver range is 80 km and the receiver heights are 100 m, 200 m, 500 m, and 1001 m above ground level. Figure 1D shows the impulse response for the four receiver heights. This result demonstrates the need to consider these channel effects when evaluating the performance of high-bit-rate systems.

IMPACT/APPLICATIONS

The goal of this work is to produce operational RF 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 the 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.

The primary payoff of this task is providing U.S. Navy and Marine Corps communicators the propagation models necessary for RF digital communications performance assessment for not only JTRS-compliant systems, but all communications systems currently in operational use. With the development of the ESPM2, the Navy and Marine Corps, as well as Army communicators, will also have a propagation model for SATCOM performance assessment to allow optimization of earth-space communications.

TRANSITIONS

All APM modifications and added capabilities transition into the Tactical EM/EO Propagation Models Project (PE 0603207N) under PMW 120 which has produced the Advanced Refractive Effects Prediction System (AREPS). Current and new software, along with information displays will also transition to PMW 120 and/or software projects for inclusion in the Naval Integrated Tactical Environmental Subsystem (NITES)-Next. Propagation modeling capabilities can also be transitioned to the Hazardous Weather Detection Display Capability (HWDDC) for use in future refractivity from clutter (RFC) integration plans.

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

Efforts under this task are related to the JTRS program and the Communication Assets Survey and Mapping (CASM) Tool. CASM is used Nationwide for planning and gap analysis of communications interoperability between state, local and Government agencies. It has been deployed to 77 urban areas across the Nation, and is expanding to statewide use. This tool was used during Operation Golden Phoenix for DoD and first responder communications planning and is currently being investigated for use by the Navy Expeditionary Combat Command, the National Communications System, First Naval Construction

Division, and the Naval Coastal Warfare Squadron, as well as other military components in Hawaii and Alaska.

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