Evaluation of Two Site-Specific Radio Propagation Models

Alakananda Paul, Paul McKenna and Frederick Najmy
Office of Spectrum Management   Institute for Telecommunication Sciences   Office of Spectrum Management
National Telecommunications and Information Administration
U.S. Department of Commerce
Phone: (202) 482-0110, Fax: (202) 482-4595, Email: apaul@ntia.doc.gov

Abstract: *This paper discusses evaluation of site-specific propagation models used in the VHF and UHF range of frequencies which are needed for prediction of coverage and interference, especially for wireless communication applications. It describes two ongoing tasks, one at the National Telecommunications and Information Administration (NTIA) and the other at the International Telecommunication Union (ITU). In the United States, two major deterministic site-specific propagation models have been used for a long time: the Terrain Integrated Rough Earth Model (TIREM) developed for the Joint Spectrum Center (JSC) of the Department of Defense, and the Irregular Terrain Model (ITM) developed by the Institute for Telecommunication Sciences (ITS) of NTIA. About two years ago, the Office of Spectrum Management (OSM) of NTIA started a task for comparison and harmonization of the two models (TIREM and ITM). Both ITS and OSM are working on this task in cooperation with JSC. Predicted propagation losses from both models have been compared with large numbers of measured data. The first order statistical results, such as mean prediction error and its standard deviation, are similar for the two models. However, errors for individual paths between the two models sometimes differ by 20 dB or more. Some of the results of the comparison task and possible explanations for the discrepancies are presented. At the ITU Radiocommunication Study Group 3 (ITU-R SG 3) on propagation, Working Party 3K decided to proceed with a Preliminary Draft New Recommendation (PDNR) on a method for path-specific propagation prediction. An outline for this document, developed in 2002, is also discussed.*

1. Introduction

Site-specific propagation models are often needed for more accurate predictions of coverage and/or interference for wireless communication systems than would be available from site-general models. Two major site-specific propagation models have been used in the United States for a long time. These are: the Terrain Integrated Rough Earth Model (TIREM), developed by Alion Science and Technology (formerly the Illinois Institute of Technology Research Institute (IITRI)) for the Joint Spectrum Center (JSC) of the Department of Defense (DOD); and the Irregular Terrain Model (ITM) developed at the Institute for Telecommunication Sciences (ITS) of the National Telecommunications and Information Administration (NTIA) of the U.S. Department of Commerce (DOC). Both of these models have been used at NTIA, and occasionally they have given different results for the same path and same physical and electrical input parameters.

ITM has an area or site-general prediction mode as well as a point-to-point (or site-specific) mode, whereas TIREM has only a point-to-point mode. Therefore, the comparison studies reported here utilized ITM in its point-to-point mode. Speaking very generally, each model is deterministic and subdivides the propagation path analysis into line-of-sight, diffraction, and troposcatter ranges, and each will calculate the dominant median excess loss contributions (i.e., relative to the free space loss) due to three possible mechanisms, line-of-sight (LOS), diffraction, and troposcatter, based on the path analysis. Both models' path analyses will obtain identical results for the terminals' radio horizon distances and the horizon elevation angles. The models differ in an important aspect in the path analysis, however, in that ITM uses it to infer the additional intermediate quantities of each terminal's effective height above its dominant reflecting plane and the interdecile range of the terrain elevations, or terrain irregularity parameter, while TIREM does not.

Both models use a two-ray approach, i.e., direct ray plus ground reflected ray, for the LOS path, though they compute the ground reflections differently. However, it appears that, when the effective heights are close to the antenna structural heights and polarization effects on the ground reflection coefficient are unimportant, both predictions are close. The same is true for the troposcatter losses, because the algorithms used in the models are similar. For diffraction paths whose lengths are less than the total smooth earth horizon distances, both models compute the loss to the radio horizon at each end of the path using the two-ray algorithm. However, the losses between the horizons are calculated differently. ITM computes the weighted combination of double knife-edge and smooth earth diffraction losses and adds a clutter loss factor based on the actual terrain. TIREM computes the loss based on the sum of diffraction losses that would result from multiple knife-edges along the path. In all of these cases, the effective antenna heights have a significant effect on ITM's predictions. Also, neither model currently supports the prediction of additional losses due to land-use/land-cover (LULC) variations along a given path.

One way to compare the models is to compare their predictions to the same measured radio propagation data. In the measurement datasets described in the next section, the excess loss relative to free space was either available or derivable, and this quantity was used for comparison to the models' predictions. In ITM, the (median) computed reference attenuation or excess (i.e., relative to free space) loss is given. In TIREM, this quantity is the difference between the calculated values of the median basic transmission loss and the free space loss. To predict losses for a given measurement, both models require the distance and terrain profile between the two terminals, heights and polarization of the antennas, frequency of operation, surface refractivity, and ground constants. TIREM also requires the atmospheric humidity.

Tasks were initiated at NTIA (the Office of Spectrum Management (OSM) and ITS) and JSC to compare the predictions given by the two models with the measured data for specific paths and to harmonize the models, if possible. This paper will discuss the results of this partially completed task.

Section 2 describes the results of the preliminary comparison of ITM and TIREM with several measurement data sets. Section 3 includes the comparison of the measured data and predicted losses using factor analysis and augmented data. Possible improvements to the models are discussed in Section 4. ITU-R Study Group 3 also has initiated a study on site-specific propagation models that will result in a *Preliminary Draft New Recommendation* (PDNR) on a method for calculating propagation losses over specific paths at VHF, UHF and SHF frequencies. The Sub-group 3K-1 has been studying different methods for two years and has defined the outline for the PDNR. This work is briefly described in Section 5. Finally, the conclusions derived from the above tasks are discussed in Section 6.

2. Univariate Comparison of ITM and TIREM to Measurement Datasets

A study [1] was performed at NTIA to determine the accuracy of predictions by the models in an effort to harmonize them. It also was performed to complement a similar study done at JSC. Thirteen different datasets containing more than 41,000 measurements were included in the study of the 20 – 10,000 MHz frequency range with various types of terrain and antenna heights. Eight of the datasets are the same as those used in the JSC study. The thirteen data sets can be classified into five groups or measurement campaigns:

i) The Phase I [2,3,4] data consisting of three datasets at HF and VHF frequencies, with various polarizations and receive antenna heights, measured at Colorado Plains and Mountain locations and in Northeast Ohio;

ii) The Phase II [5,6,7,8,9] data consisting of five datasets at VHF, UHF and SHF (as many as seven) frequencies and 13–24 discrete receive antenna heights measured at four locations in Colorado and at the Virginia Piedmont region;

iii) The Low Antenna data [10] consisting of three datasets measured in Idaho, Washington and Wyoming at 230 and 416 MHz at two low transmit antenna heights and four low receive antenna heights;

iv) The Fort Huachuca data provided by JSC and measured at Fort Huachuca, Arizona for 60 MHz and fixed transmitter and receiver antenna heights of 10 and 2 m respectively;

v) The TASO (Television Allocations Service Organization) data [11] from an FCC website consisting of measurements of FM radio and TV broadcast signals for a variety of locations in the continental U.S. in the UHF and VHF bands.

In all of the measurement campaigns except iv) and part of v) above, many paths were observed and multiple measurements were attempted per path. In consequence, though many measurements are considered here, a very large amount of the data is correlated; hence, care must be taken when using the data in a statistical context. However, the data provide useful information about height gain, frequency dependence, clutter losses, etc.

The preliminary results of the models' prediction errors (i.e., $L_{predicted} - L_{measured}$) are summarized in Table 1 in terms of the overall datasets' means, standard deviations, skewnesses, and excesses, along with the standard errors of these quantities. The values in parentheses are the corresponding results from the JSC study. In general, there were reasonable agreements between the statistical results of the two studies. In view of the correlated nature of the measurements and the predictions, however, further analysis is required.

3. Comparison of Prediction Errors Using Factor Analyses

As its title suggests, the analysis described in Section 2 is univariate, i.e., it assumes that the prediction error associated with each measurement is independent of every other measurement and identically distributed as the population of the universe of tropospheric radio circuits. However, when the data/prediction errors are correlated, it is necessary to generalize the concepts of mean and variance statistics and do a multivariate analysis [12]. The correlation model adopted here is that data and predictions for different paths are assumed independent, while data and predictions for the same path are not.

In this phase [13], eleven datasets containing more than 18,000 measurements were used. Five obviously erroneous TASO paths were excluded, and missing data were augmented with maximum likelihood estimates using the E-M algorithm. The augmented datasets were subjected to factor analyses based on the eigenvalues and their corresponding eigenvectors of the datasets' prediction errors covariance matrices, formulated on the correlation model described above. In general, it was found that the factors in the measurement datasets correspond to the propagation path, antenna heights, frequency, and polarization. The factor analysis determines how much of each of these eigenvalues contributes to the total variance (i.e., the trace of the covariance matrix) of the prediction errors of the models. The weighting of each of the elements of the corresponding eigenvector determines how the factors contribute to the prediction errors. Appendices I-III of [13] summarize the results of the models' prediction error mean vectors and covariance matrices, and the corresponding ordered eigenvalues and eigenvectors for the Phase I, Phase II (VA only), Low Antenna and TASO datasets. Appendices I, II, and III of [13] summarize the results for both models using 100 m, 200 m and 450 m extraction intervals respectively, using both available and augmented data. In most cases, the total variances of both models decrease with increasing extraction intervals. Appendices Ia, IIa, and IIIa of [13] similarly summarize the results for the augmented data for the same three extraction intervals.

Table 2 gives a summary of the percentages of the datasets' total variances of the errors due to the two largest factors. For every dataset and both models, the first factor always corresponds to the propagation path. The second factor varies among datasets and models; it is sometimes frequency and sometimes antenna height. However, for both models, the propagation path accounts for a large percentage of the error variance. For the results reported here, ITM predictions have been obtained using effective antenna heights above the effective reflecting surface, whereas TIREM uses structural antenna heights.

4. Improvement and Harmonization of the Models

Results of the two studies done at NTIA indicate that sometimes ITM's predictions are more accurate when the effective antenna heights are used, and there are other cases where ITM's predictions are more accurate if the structural antenna heights are used. However, ITM predictions are most erroneous when effective antenna heights are much larger than the structural antenna heights. In the case of TIREM, use of structural heights gives good predictions in some cases. However, in other cases, the use of effective antenna heights may be called for.

In the study mentioned above, the ITM program was used to examine the effective antenna height behavior. Propagation loss predictions were made by using the effective antenna height calculation currently in use and by using structural antenna heights. Both of these methods fail to give low prediction errors in all cases. In fact, in many cases, the optimum value of the effective antenna height is somewhere between the structural antenna height and the effective antenna height calculated by the current ITM algorithm. This is indicated by the prediction errors being positive in one path's measurement and negative in another's. Since the propagation path is the primary factor contributing to the prediction errors, and the effective height calculations depend on the path's terrain profile, it is intuitive that an optimum way of calculating the effective antenna height will most likely reduce ITM's prediction errors. In addition, greater prediction accuracies could accrue from more information for the propagation path, such as LULC, vegetation, buildings, clutter, etc.

5. ITU-R Work on Site-Specific Propagation Models

At the ITU-R Study Group 3 on propagation, there have been discussions regarding site-specific propagation models. In 2000, the U.S. Administration submitted ITM to be considered as the source of a new recommendation. However, a model was also submitted from Germany which has been used for mobile communications in Europe. Therefore, ITU-R Working Party 3K formed an international correspondence group to study these models and compare them to results obtained from measured data as well as to results obtained from ITU-R Rec. P.452, which is used to predict site-specific interference between terrestrial stations between 700 MHz and 40 GHz.

After considerable deliberations over the next two years, the Subgroup 3K-1, responsible for path-specific propagation prediction methods, decided to initiate a new PDNR which will provide guidance for the prediction of path loss and field strength for terrestrial propagation over specific paths from 1 to 1500 km at frequencies of 30–5000 MHz. The models will be deterministic with empirical adjustments to account for clutter and variability. Delay spread also will be considered. Two dimensional terrain profiles will be used with minimum resolution of 1 km and maximum resolution of 50 m.

6. Conclusions

Evaluation of path-specific models both in the U.S. and at the ITU has offered much insight into propagation prediction methods. Important factors for this evaluation include the availability of 'good' measurement data and understanding the nature of its underlying regression, when it exists. For the U.S. measurement datasets considered here, the variances of the two models' prediction errors predominantly depend on how well or poorly the path is modeled. Therefore, good terrain data and better information about the particulars of each path are important for reducing models' prediction errors, in addition to improving the quality of the physical approximations used in the models. Additional information regarding vegetation, buildings, urban clutter, ground constants, atmospheric refractivity, etc., seems also to be needed. For ITM and, perhaps, for TIREM, an improved/optimized effective antenna height algorithm holds some promise of effecting some of this reduction. The work at the ITU will be based on many of these factors plus contributions from other countries based on their data and experience.

7. References

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Table 1. Comparison of Overall Dataset Prediction Error Statistics for ITM & TIREM

Data	No. of meas.	ITM mean (dB)	TIREM mean (dB)	ITM std. dev. (dB)	TIREM std. dev. (dB)	ITM skew-ness	TIREM skew-ness	ITM excess	TIREM excess
CO. MTNS.	550 (286)	-17.1 +/- .7 (-22.8)	-4.4 +/- .6 (-4.5)	16.2 +/- .5 (12.1)	13.7 +/- .4 (15.0)	.6 +/-.1	.0 +/-.1	.5 +/-.2	-.1 +/-.2
CO. PLNS.	1983 (1983)	-14.9 +/- .2 (-16.7)	-4.4 +/- .2 (-5.6)	10.2 +/- .2 (10.3)	9.9 +/- .2 (9.8)	0.0 +/-.1	.1 +/-.1	.4 +/-.1	.4 +/-.1
NE OH.	1787 (1787)	-10.1 +/- .2 (-12.7)	0.0 +/- .2 (-.2)	9.2 +/- .2 (8.7)	9.6 +/- .2 (8.7)	0.0 +/-.1	.1 +/-.1	.4 +/-.1	.1 +/-.1
R-1	6780	2.0 +/- .2	1.2 +/- .1	13.9 +/- .2	12.0 +/- .1	.8 +/-0.0	-.2 +/-0.0	2.5 +/-.1	.8 +/-.1
R-2	2458	-7.5 +/- .5	-18.4 +/- .4	25.7 +/- .3	20.8 +/- .3	-.2 +/-0.0	-.6 +/-0.0	-.3 +/-.1	.0 +/-.1
R-3	5149	1.9 +/- .2	2.8 +/- .2	11.6 +/- .2	11.4 +/- .1	.9 +/-0.0	.2 +/-0.0	3.1 +/-.1	.4 +/-.1
R-4	9498	-12.8 +/- .2	-14.1 +/- .2	16.6 +/- .2	16.6 +/- .1	-.4 +/-0.0	-.8 +/-0.0	1.3 +/-.1	.3 +/-.1
VA.	1655 (1871)	-.9 +/- .3 (-3.7)	-.2 +/- .4 (1.8)	13.2 +/- .3 (9.6)	15.6 +/- .3 (10.8)	-.2 +/-.1	-.2 +/-.1	1.5 +/-.1	.2 +/-.1
ID.	435 (435)	-17.5 +/- .7 (-15.4)	-10.9 +/- .6 (-8.7)	14.5 +/- .4 (12.7)	11.9 +/- .4 (11.3)	-.3 +/-.1	-.4 +/-.1	-.4 +/-.2	-.2 +/-.2
WA.	892 (892)	-2.4 +/- .4 (-5.7)	5.1 +/- .4 (4.7)	12.8 +/- .3 (11.7)	12.0 +/- .3 (13.2)	.3 +/-.1	.1 +/-.1	.1 +/-.2	.2 +/-.2
WY.	704 (704)	-11.9 +/- .6 (-15.8)	-6.8 +/- .5 (-5.5)	14.6 +/- .4 (12.6)	12.5 +/- .3 (9.7)	-.1 +/-.1	0.0 +/-.1	0.0 +/-.2	-.2 +/-.2
Ft. Hua.	372 (420)	-3.0 +/- .6 (-5.4)	11.4 +/- .3 (7.8)	11.5 +/- .3 (11.3)	6.0 +/- .2 (5.9)	-.5 +/-.1	-.2 +/-.1	-1.2 +/-.3	-.9 +/-.3
TASO	8865	-3.2 +/- .1	-1.2 +/- .1	12.5 +/- .1	14.0 +/- .1	-.2 +/-0.0	-.5 +/-0.0	2.3 +/-.1	.7 +/-.1

statistic
+/- std. error
(JSC statistic)

Table 2. Percent of Error Variance due to First and Second Factors

	ITM		TIREM	
Dataset	**First**	**Second**	**First**	**Second**
Phase I, CO mountains	85	7	78	12
Phase I, CO plains	84	6	79	8
Phase I, NE Ohio	72	9	67	11
Phase II, Virginia	81	8	60	19
Low Antenna, Idaho	89	5	93	4
Low Antenna, Washington	93	3	93	4
Low Antenna, Wyoming	93	4	87	6
TASO, t2_nb	91	9	82	18
TASO, t8	87	7	74	17
Average	**86**	**6**	**79**	**11**