Comparison of Measurements with Prediction Methods for Propagation by diffraction at 88 - 108 MHz

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***Abstract*—Three methods for predicting attenuation due to diffraction are tested against a large database of 115614 measurement points, representing 115614 different path profiles of 100-meter horizontal resolution, and vertical root mean square error of about 6 meters. The signal level at each geographic measurement point is calculated as the median of about 40 basic measurements, and the measurement database is thus reduced from about 4 million basic measurements. The mobile measurements are taken from main FM (88- 108 MHz) broadcasting emitters located in southern Norway, and the corresponding broadcasting antenna diagrams have been measured by helicopter. Path profiles are categorized by number of terrain obstructions between emitter and receiver, in order to study their effect on each propagation loss method. The current ITU method and Picquenard's construction, with a variable number of included terrain obstructions, are compared with the measurements, and difference statistics are calculated. A particular version of Picquenard's construction is shown to be better than the current ITU method in terrain of Norwegian type. This new method is, in contrast to the ITU method, within the estimated expected errors resulting from using Norwegian digital terrain elevation data.**

***Index Terms*—Propagation, diffraction, measurement, broadcasting.**

I. Introduction

PROPAGATION due to diffraction is particularly important for radio services operating between 30 and 1000 MHz. Therefore there are many software tools that implement one or more of the diffraction models. Each model is usually tested against a limited set of measurements, due to time or financial constraints. It is in any case likely that only a few typical terrain profiles have been used to verify the model. The question is then whether the models are valid for all kinds of terrain.

The main focus of this paper is to demonstrate an automated method for propagation measurement and analysis, which is used to obtain measurements involving a wide variety of paths.

Manuscript received March 24, 2003. This work was supported in part by the Norwegian Post and Telecommunication Authority, and in part by the Norwegian Defense Research Establishment.

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In this paper basic measurements are referred to as the 40 measurements of which the median defines a measurement point. A large database of 115614 such measurement points and terrain profiles are used to test three propagation methods. One of the methods is widely used and recommended by the International Telecommunications Union (ITU) and therefore important. The current ITU general method for diffraction [1] is based on studies over many years, conducted by scientists skilled in the field. It is based on Deygout's construction, but differs slightly in the line-of-sight case, and includes terms fitted empirically. ITU models are developed through discussion and verification against terrain profiles and measurements that are kept by the ITU in a large database. The database relevant to diffraction, supported by ITU-R SG3, contains a few thousand measurements, mostly contributed by the UK, USA and Germany. Thus we may expect models based on these data (as well as additional measurements) to be quite good. The second method that will be tested is Picquenard's construction [2]. It is chosen because it is easy to understand and uses no empirical corrections. It is also straight forward to extend the Picquenard model and fit it empirically to take a selected number of terrain obstacles into account. Therefore a third and new, fitted, method is tested, based on Picquenard, which includes a limited number of terrain obstacles.

We are describing the equipment and measurement campaign in Section II. In Section III we explain the methods deployed for data reduction and quality assurance. In Section IV we compare measurements with predictions. Probable causes for differences are discussed in Section V. Finally, conclusions and suggestions for further work are contained in Section VI.

II. Measurements

Measured emitters were FM broadcasters, mounted in high towers and emitting powers of a few kW at specific frequencies in the range 88 MHz to 108 MHz. The different emitters at each tower and frequency have antenna patterns measured by helicopter, and these antenna gains are taken into account in the calculations.

The field strengths were measured using a Rohde & Schwarz ESVB receiver. A Garmin GPS receiver was used

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together with a compass and a wheel mounted counter for accurate navigation (+/- 50m). The equipment was placed in a Toyota HiAce van, with a crossed dipole receiver antenna mounted one meter above the roof, i.e. three meters above the road. The GPS antenna was mounted directly onto the roof. The resultant antenna diagram of car + antenna was measured by driving in large circles on a plateau from which there was a clear line-of-sight to a strong broadcasting emitter. Also the receiver antenna gains have been corrected for in the calculations.

All instruments were controlled by a Kontron PC and software developed by Kathrein.

It was possible to measure up to 10 frequencies simultaneously at a rate of about 1 measurement at every chosen frequency per meter. In [3] it is suggested that measurements that are separated by more than about 0.38 wavelengths have a cross-correlation coefficient of less than 0.3. This corresponds to approximately 1 meter at 100 MHz, suggesting that our basic measurements are just spaced far enough apart to be mutually independent.

In order to enable a post processing quality check, we measured two different frequencies from each broadcasting tower. We could thus do simultaneous measurement of signals from a maximum of 5 different towers.

The measurements were conducted in southern Norway in a wide variety of terrain profiles, ranging from rolling planes in the southeast, to predominantly mountainous terrain and fjords along the northwest coast. The mountains are frequently 1000-2000 meter high, and some run steeply down into fjords.

Each measurement series typically contains data from 1-3 hours driving, which corresponds to 50-150 km traveled distance. Usable signals were obtained for distances up to about 100 km. The measurements were mostly made on country roads, with few neighboring man made objects.

III. Post processing of measurement data

It is not possible to catch individual measurement errors by manual methods, and automatic post processing is therefore necessary in order to check the quality of such a large measurement base.

For each broadcasting tower we have compared the measured powers at two different frequencies over approximately 40 meters (40 basic measurements). From the distribution of the 40 observed field strengths, each series is accepted only if the 10 % value is 10 dBμV or larger, and the 90 % value is less or equal to 95 dBμV. Also, if the difference between the medians of the two series is greater than 10 dB, the measurement point is tagged with a special code. This ensures that we can track possible invalid measurement points caused by interference from other emitters.

The medians for each frequency over the 40 basic measurements are then used to represent the measurement point every 40 meters, and we have thus effectively reduced the amount of data points by a factor of 40, from about 4 million measurements to 115614.

IV. Comparing measurements with models

We have chosen to use the Root Mean Square Error (RMSE) as an absolute measure of how well the different propagation models fit the measurements. A systematic deviation from zero of the mean of the difference between modeled and measured propagation loss will increase the RMSE. In order to investigate the symmetry of the errors, we have also calculated the 0.1, 1, 10, 50 (median), 90 and 99.9 % occurrences of the differences.

Complete measurement series that clearly and consistently contain errors, either due to incorrect broadcasting antenna diagram, or due to interference or other systematic errors, are excluded from the comparison analysis.

A. Picquenard's model

The Picquenard diffraction construction [2] is essential to the following discussion, and the details are therefore illustrated in Figure 1.

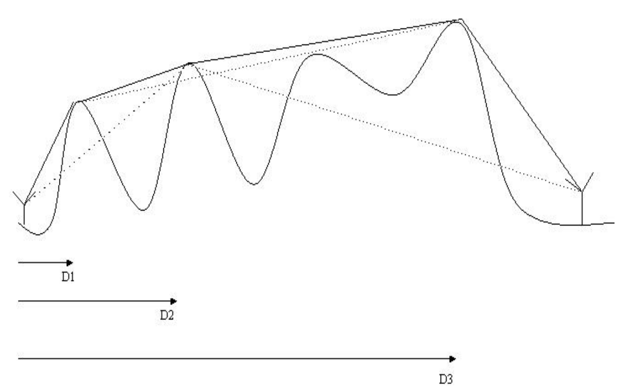

Fig 1. Picquenard model for calculation of diffraction losses

The path profile is corrected for earth curvature, using 4/3 earth-radius. Three diffraction losses, from peaks at distances D1, D2 and D3, are calculated for the example path of Fig 1. In addition a below line-of-sight diffraction loss has been calculated between the emitter and its nearest obstacle, and between the receiver and its nearest obstacle. The calculations can in principle be extended to any number of terrain obstacles.

For the purpose of comparing models and measurements we have categorized the propagation paths according to the number of obstacles found using the Picquenard construction. We have thus obtained statistical parameters for the RMSE and for deviations of the propagation loss calculations for

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each of paths having 0 obstructions, 1 obstruction, 2 obstructions, etc, up to and including 9 obstructions.

We have studied two different versions of the Picquenard model. One of them takes all terrain obstacles into account. This is the general Picquenard model. The other takes the biggest diffraction term into account, and adds 0.67 multiplied with the next biggest diffraction term. We will refer to this method, which only takes two terms into account, as Picquenard 1,67.

There is a slight difference between Picquenard's way of defining obstructions and the ITU method. In order to compare the different propagation methods for similar paths (categorization), we will always be referring to the number of obstacles found using the Picquenard algorithm.

B. ITU model

The ITU model is well described by [1], and the details are not reproduced here. The main idea is that it is based on Deygout's model and that a maximum of three main obstacles in the propagation path are used. In the case of line-of-sight propagation it differs from the Deygout construction in that two secondary edges are still used in cases where the principal edge results in a non-zero diffraction loss.

Deygout's method considers the whole path, determines the 'main edge', and divides the path at both sides of the 'main edge' into sub-paths, where subsidiary 'main edges' are found, etc, in a hierarchical way. Picquenard's method calculates all diffraction terms from all edges from emitter to receiver, and considers all contributions. The main difference between the methods is that all diffraction terms are considered by the Picquenard method, while some important terms can actually be missed out due to the hierarchical structure of the Deygout method.

C. RMSE comparison

The RMSEs for the ITU model, the general Picquenard model and the Picquenard 1,67 model are summarized over all measurement series in Table 1.

We note that the Picquenard 1,67 construction is better than the ITU construction for any number of obstacles in the path between emitter and receiver. The RMSE of the ITU model is generally increasing with the number of obstacles in the propagation path. This results in an overall better RMSE performance of Picquenard 1,67 of about 2.7 dB compared to the ITU model.

D. Distribution of prediction errors

Tables II-IV give different percentiles of predicted – measured propagation attenuation values, in dB. These tables are useful both for checking the distribution of errors, but also in order to establish safety margins. The optimistic values (low percentage) may be used for interference protection, while the pessimistic values (high percentage) may be used for communication establishment.

TABLE I
RMSE (IN DECIBELS) FOR THE ITU MODEL, THE GENERAL PICQUENARD MODEL AND THE PICQUENARD 1,67 MODEL

RMSE (dB)	ITU model	Picquenard (all diffraction terms included)	Picquenard (1,67 diffractions included)	-	**Number of observations**
line-of-sight	9.1	8.5	8.5	-	10920
1 obstacle	11.5	8.2	8.3	-	27742
2 obstacles	11.6	12.5	9.1	-	35345
3 obstacles	12.2	23.9	9.5	-	23696
4 obstacles	12.5	37.5	9.6	-	11333
5 obstacles	13.1	51.8	9.4	-	4501
6 obstacles	13.3	65.9	9.5	-	1506
7 obstacles	13.4	82.0	8.7	-	411
8 obstacles	12.7	95.7	7.8	-	118
9 obstacles	14.7	112.7	6.8	-	37
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Overall	**11.7**	**22.9**	**9.0**	-	**115614**

From the 50 % (median) value of Table III we see that the general Picquenard method with all obstructions included is very pessimistic, especially for paths of many obstructions. All knife-edge diffraction methods, like Deygout and Picquenard, are based on very simplified assumptions about possible radio wave paths from emitter to receiver. However, the emitted radio waves are distributed across space and will follow paths of least resistance, so that in practice it is found that only a few (3 or less) important diffractions should be taken into account. The particular inclusion of terms in the Picquenard 1,67 method was chosen because it gave an optimum fit to the measured data (smallest RMSE) in the presence of an arbitrary number of obstacles in the path.

The median value of the Picquenard 1,67 method is slightly optimistic, as can be seen in Table IV, independently of the number of path obstructions.

From Table II we see that the ITU model is optimistic for up to, and including, 4 terrain obstacles. For more complicated paths also the ITU model becomes pessimistic, while its overall performance remains optimistic.

It is also possible to compare the overall performance of the models without doing paired comparisons between model and measurement. In Fig 2 we have plotted the cumulative distribution of predicted propagation loss relative to an arbitrary threshold, minus the cumulative distribution of the measured loss relative to the same threshold, employing the different models discussed in this paper. In this way we have averaged out some of the uncertainty associated with vehicle positioning and the uncertainty associated with the digital terrain elevation database. The low percentages in Fig 2 are thus representing high attenuation.

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TABLE II
DIFFERENT PERCENTILES OF DIFFERENCE (IN DECIBELS) BETWEEN ITU MODEL AND OBSERVED ATTENUATION

Pred-Obs (dB)	0.1%	1%	10%	50%	90%	99%	99.9%
line-of-sight	-31.5	-23.5	-10.8	-2.4	4.6	7.3	8.9
1 obst	-20.9	-8.3	-2.1	-6.9	2.9	11.9	17.2
2 obst	-25.8	-22.1	-15.5	-5.9	6.5	18.6	23.9
3 obst	-25.1	-21.6	-14.7	-3.6	10.9	22.1	27.0
4 obst	-21.9	-19.7	-12.7	-1.2	13.2	23.2	26.1
5 obst	-19.3	-17.8	-10.7	1.2	14.8	23.9	25.4
6 obst	-14.7	-14.2	-8.5	2.0	16.0	22.0	22.4
7 obst	-7.4	-7.4	-4.1	5.1	16.2	21.1	21.1
8 obst	-1.0	-1.0	-0.1	5.8	13.0	14.0	14.0
9 obst	5.7	5.7	6.8	12.2	17.1	17.3	17.3
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Over all	-24.1	-18.3	-11.1	-4.4	7.5	17.4	21.8

Fig 2 confirms our previous conclusions from Tables II-IV that the ITU on average is optimistic except for high attenuation values. Our Picquenard 1,67 method is neither overly optimistic nor pessimistic for any percentage of the measurements. The mean value of difference to measurements of Picquenard 1,67 in Fig 2 is –0.3 dB, while it is –4.0 dB for the ITU model.

V. DISCUSSION OF DIFFERENCES BETWEEN MODELS AND MEASUREMENT

The simple diffraction models treated in this paper are very inexact representations of how radio waves propagate over terrain. The following discussion treats some quantifiable terms that contribute to errors, but other effects, especially due to spreading of the signal along its path, may be equally important.

The standard deviation taken over the 40 basic measurements, of which the median is the basis for each of our compared measurement points, is approximately 3.0 dB. Since we are using the median, fast fading is not a prime source of errors.

Refractivity variations in the atmosphere might be a source of errors, since such variations will affect the effective earth radius of the propagation path. In a paper by Vogler [4] it is shown that at 100 MHz the effect of refractivity is much smaller than at higher frequencies. For an example path with five terrain obstacles, he has shown that a variation of surface refractivity N_s between 200 and 400 causes a maximum of about 3 dB differences in attenuation. Refractivity variations this huge are not likely.

TABLE III
DIFFERENT PERCENTILES OF DIFFERENCE (IN DECIBELS) BETWEEN GENERAL PICQUANARD MODEL AND OBSERVED ATTENUATION

Pred-Obs (dB)	0.1%	1%	10%	50%	90%	99%	99.9%
line-of-sight	-30.0	-21.6	-9.1	-1.2	5.5	8.0	9.8
1 obst	-15.5	-5.4	-1.1	-0.15	8.3	13.9	17.6
2 obst	-13.8	-9.4	-2.5	7.3	19.0	28.4	32.8
3 obst	-6.0	-2.2	5.9	18.9	35.5	47.0	51.6
4 obst	4.1	7.7	16.7	32.4	52.2	66.3	69.8
5 obst	16.2	18.4	28.9	47.3	68.6	81.4	83.9
6 obst	31.6	32.7	41.1	59.9	86.0	95.2	96.0
7 obst	52.5	52.5	56.8	78.4	102.0	106.8	106.8
8 obst	74.9	74.9	78.7	91.7	106.5	109.1	109.1
9 obst	91.4	91.4	98.9	110.1	126.1	126.8	126.8
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Over all	-10.2	-4.5	2.9	12.1	25.0	33.8	37.6

TABLE IV
DIFFERENT PERCENTILES OF DIFFERENCE (IN DECIBELS) BETWEEN PICQUANARD 1,67 MODEL AND OBSERVED ATTENUATION

Pred - Obs (dB)	0.1%	1%	10%	50%	90%	99%	99.9 %
line-of-sight	-30.0	-21.6	-9.1	-1.2	5.5	8.0	9.8
1 obst	-16.0	-5.9	-1.2	-0.9	7.4	12.9	16.4
2 obst	-18.4	-14.9	-8.8	0.3	10.7	18.9	22.7
3 obst	-18.9	-15.8	-9.8	-0.6	10.7	18.4	21.4
4 obst	-17.2	-15.4	-9.8	-1.0	9.6	16.6	18.7
5 obst	-15.7	-14.7	-9.7	-1.0	8.1	15.2	16.7
6 obst	-13.7	-13.0	-9.3	-1.8	8.0	13.0	13.4
7 obst	-8.9	-8.9	-6.5	-0.3	6.7	10.2	10.2
8 obst	-5.1	-5.1	-4.8	-1.7	2.9	3.4	3.4
9 obst	-2.6	-2.6	-2.6	1.7	5.2	5.9	5.9
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Over all	-18.7	-13.5	-7.3	-0.5	9.2	15.8	18.9

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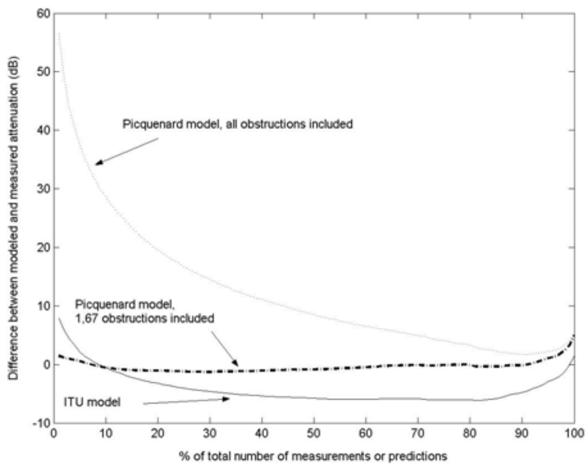

Fig. 2. Cumulative distribution of predicted propagation loss relative to an arbitrary threshold, minus the cumulative distribution of measured loss relative to the same threshold

One of the main reasons for a high RMSE between models and measurement is probably the variation in the terrain elevation data close to the receiver. The height of the receiving antenna above surrounding clutter will vary randomly and create a high RMSE. This variation will have little effect on the diffraction calculations (the difference is found for most paths to be less than 1 dB), but it will influence the measured values. A Norwegian Master degree thesis [5] has shown that the expected RMSE value of the Norwegian digital terrain elevation data is on average approximately 6 meters in height, but may in some cases be up to 18 meters. For simplicity, and as a first approximation, we have assumed that these errors are of the same sizes as the unpredictable variation in effective antenna height near the receiver. The Okumura-Hata [6] method for mobile propagation contains a term for the height-gain of an antenna. This is strictly only valid for frequencies between 150 MHz and 1500 MHz, but we have adopted it due to its simple form:

$$a(H_2) = (1.1\log f - 0.7)H_2 - (1.56\log f - 0.8) \qquad (1)$$

f is in units of MHz, H_2 in meters, and a in dB. We will regard a variation in elevation data near the receiver antenna to be equivalent to a variation in effective receiver antenna height. By differentiating a with respect to H_2, we get the following expression for the uncertainty in propagation loss due to effective antenna height, Δa, as a function of the uncertainty ΔH_2 in height:

$$\Delta a(\Delta H_2) = (1.1\log f - 0.7)\Delta H_2 \qquad (2)$$

Using (2) at 100 MHz for the mobile antenna, the 6 meters RMSE in height lead to an expected 9 dB RMSE in attenuation.

The power, feed loss and antenna gains of the broadcasting emitters may be slightly varying. However, it is unlikely that this will cause an overall extra variation of more than 2 dB standard deviations.

We are then left with our GPS navigational error, which may cause an additional height error. This error may, at the accuracy of GPS reception in 1995, have been up to 50 meters, which will account for 1-2 meters additional error in height, which again can be translated to additional 2 dB RMSE.

Adding these error terms in quadrature causes the overall expected RMSE to rise to approximately 9.5 dB.

For the ITU model we found an overall RMSE of about 11.7 dB, and for the Picquenard 1,67 diffraction model an overall RMSE of about 9.0 dB. The Picquenard 1,67 is thus within the expected RMSE, while the ITU model has larger RMSE than we would expect from just looking at error sources we have discussed here. There must therefore be an additional error term due to the ITU model itself. The extra RMSE term, added in quadrature, will have to be of the order of 8 dB in order to result in the total of 11.7 dB RMSE for the ITU model.

In a paper by Tzaras and Saunders [7], propagation models and measurements have been compared in a similar way for the UK. In that paper standard deviations of errors ranging from about 6 dB to about 10 dB were reported, depending on the number of terrain edges and the chosen diffraction model. There are several reasons why those results cannot be compared directly to the error statistics of this paper. Firstly, the UK terrain profiles are probably very different from the Norwegian ones. Secondly, we don't know the expected error of the UK terrain elevation data, but we may assume smaller errors than for the Norwegian terrain elevation data. Thirdly, we have shown that, due to the Okumura-Hata height correction term, we will expect the errors to depend on frequency, which in [7] varies between 40 MHz and 900 MHz. However, the mean errors may be compared. These were reported in [7] to range between –1.8 and –3 dB, while our Picquenard 1,67 method has a mean error of about –0.5.

VI. Conclusion

By comparing propagation models with a large set of measurements, we have found the current ITU model to be optimistic, and to have a bigger RMSE than the simpler Picquenard 1,67 model. The successful simpler model employs only the two largest diffraction contributions, and does not rely on additional empirical fitting of parameters. It is found to be within the expected error contributed by the RMSE of the Norwegian digital terrain elevation data.

The ITU method, which is based on the Deygout method, has been used as a baseline for comparison for the Norwegian measurements. The improvement of the new Picquenard 1,67 method over the Deygout/ ITU implementation for paths of many obstructions is about 4-5 dB better in RMSE, in Norwegian terrain. The slope-UTD method of [7] is shown to

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be superior to the Deygout method in UK terrain, showing about 2.5-3 dB better standard deviation of error. The frequencies used for the experiments in UK and Norway are different, and in future work it would therefore be interesting to compare directly the performance of the Picquenard 1,67 model to the more physical slope-UTD solution.

Other future work could be to test the new Picquenard 1,67 implementation at other frequencies than 88 – 108 MHz. It may well be that the optimal fitted inclusion of diffraction terms is different at other frequencies.

Categorization of propagation paths by the number of obstructions has proved to be a good way of studying the success of different propagation models.

When conducting automated propagation measurements, it is important to include extra measurements for quality assurance.

Acknowledgment

The Norwegian Post and Telecommunications Authority is thanked for letting the author continue to work with the data after leaving as their employee.

Georg Lothe is thanked for his contribution to the measurements and the post processing of data.

The reviewers and Terje Tjelta are thanked for their useful comments.

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DOI til publisert versjon / DOI to published version: 10.1109/TAP.2004.829405