

DIGITAL TERRAIN DATABASE STRUCTURES AND ACCURACY REQUIREMENTS FOR PROPAGATION MODELING

Harry R. Anderson, MSc., P.Eng.
EDX Engineering, Inc.
P.O. Box 1547
Eugene, Oregon 97440
Tel: (503) 345-0019 Fax: (503) 345-8145

Abstract - Digital terrain elevation model (DTEM) databases are essential for realistically calculating path loss and coverage areas for radio communication systems of all types. Because such propagation models are well-suited to computer programs, the factors determining efficient DTEM data structure and necessary DTEM data accuracy are largely derived from the requirements of the computerized propagation models. The first part of this paper discusses DTEM data structures for efficient elevation retrieval. The second part examines the required DTEM accuracy needed to achieve acceptable path loss results given commonly-used diffraction loss propagation primitives. The results show that obstacle elevation errors on the order of 15-25 meters can be tolerated before calculated path loss changes by more than about 2 dB on obstructed paths.

1.0 DTEM Database Structures

DTEM's are generally organized in two forms - vector format and raster or grid format. Vector databases are collections of vectors usually describing elevation contours where vector endpoints have equal elevation, or constant slope vectors in which the vector endpoint elevations are different. Vector databases are often the direct product of digitizing topographic maps. Unfortunately, they are inefficient to use in computer programs because there is no simple mapping from geographic position to DTEM database position due to the non-uniform density of the vector data. Grid format DTEM's are therefore almost universally used with propagation software because there are simple mapping algorithms which relate geographic position to the location of the data point in the database.

For most currently used propagation models, path loss is predicted using a 2 dimensional (2-D) terrain profile between the transmitter and the receiver. The 2-D profile follows the radio path from transmitter to receiver forming a sector of a great circle path on the earth's surface. To construct a terrain profile, the

terrain database must be repeatedly accessed to find elevation values along the great circle path. For a typical area-wide propagation study, 360 radial paths may be used extending out from the base station transmitter and spaced every degree in true azimuth. If the study radials are 50 km long (a typical value for cellular base station studies), and the point spacing along each radial is 0.1 km, a total of 180,000 elevation points must be extracted from the database. For a composite study with dozens of base stations, literally millions of elevation points along study radials are required. It's therefore worthwhile to make terrain extraction algorithms as efficient as possible.

The points along a terrain profile great circle path are conveniently defined by a latitude-longitude pair. As the extraction process moves out along a radial, the latitude-longitude location of each point is calculated using spherical trigonometry, the radial azimuth, the point distance, and the base station latitude-longitude coordinates.

With the latitude-longitude position of the point known, the next step is to determine the position in the database where this point occurs. In general, terrain elevation databases will consist of sets of datafiles, each of which covers a defined geographical area. Within each datafile the elevation points are usually arranged in a simple row-column matrix format such that the geographical position of an elevation point is conveyed by the row-column position in the matrix. The terrain elevation lookup process essentially is the process of answering three questions about the location of the point: 1) which datafile?, 2) which row?, and 3) which column?

The datafile question can be easily answered in one of two ways. Where the database has a uniform, homogeneous structure, the datafile names themselves can convey the area covered. For example, for a 20 km x 20 km data tile in Great Britain, the tile with southwest corner National Grid coordinates of x=300000, y=100000 could have a file name such as EDX30010.TER. The "30" is the x position of the

southwest corner; the "010" is the y position. The next file east would be named EDX32010.TER. The next file north would be named EDX30012.TER, and so forth. With such a pre-defined file name structure, it is only necessary to translate the latitude-longitude at the desired point into National Grid coordinates, construct the file name using the coordinates rounded off to 20 km intervals, open the file, and read the data.

If the files in the database are non-uniform, it is necessary to use a "header" record in each file which contains the coordinates of the corners of the area which the datafile covers. The information in the headers for all files is read and cataloged when the propagation program is started so that finding the appropriate file during the terrain extraction process involves a quick search through the cataloged header information.

Since the desired elevation point coordinates are known in terms of latitude-longitude, finding the right row and column in the datafile matrix is most rapidly done when the grid of points are at even latitude-longitude intervals. The 3 arc second database covering the United States is such a database. Finding the correct row and column numbers is a simple matter of subtracting the latitude-longitude of the corner from the latitude-longitude of the subject point, and dividing by the grid point spacing in geographical seconds.

Usually the desired point does not fall directly on a grid location so that it's necessary to find surrounding grid points and performing an interpolation among them. Several simple and elaborate schemes have been used or suggested for this interpolation problem, but simply using the four surrounding corner points and linear interpolation has been shown to be about as good as any approach [1], and is certainly computationally efficient since it only requires a one row or column shift to find the necessary four points.

When the datafile does not use a regular latitude-longitude spacing but a linear x,y spacing in meters such as the 50 meter terrain databases for Great Britain, a further translation step is needed for each extracted point. This extra step converts the latitude-longitude position to the linear x,y coordinate system on which the datafile is based. This translation requires knowledge of the map projection and particular earth ellipsoid constants. In our work we've found the Transverse Mercator conversion formulae for ellipsoids as found in [2] accurately perform this coordinate translation when the particular earth radius, eccentricity, and projection biases are

used in the conversion operations. Latitude-longitude to UK Nation Grid coordinate conversion is typically with 1 meter of known results using this method. This is certainly adequate accuracy for the terrain lookup process.

Because the linear x,y datafile arrangement requires the extra conversion step, (and the conversion calculations are non-trivial), from a computational viewpoint the latitude-longitude grid structure is preferable to the linear x,y arrangement. The disadvantage, of course, of the latitude-longitude coordinate system is that it is not linear on flat maps and thus more difficult for people to use when manually determined coordinates. By contrast, linear x,y systems are easy to use for manual coordinate determination.

2.0 Radial Line versus Regular Grid Propagation Studies

An issue which frequently arises is the relative merits of radial line and regular grid propagation studies.

In a radial line study, elevation points are found along radials emanating from the transmitter site. Path loss calculations are then done to each point on each radial. The results are then plotted in a variety of ways such as multi-colored radial lines where the color indicates the field strength. Alternately, the ensemble of radial line path loss results can be mapped into a regular grid for a colored grid display, contouring, etc. This is a computationally efficient approach both for terrain data extraction and for path loss calculations, especially if recursive techniques are used to compute diffraction loss as the study proceeds out along a radial. The drawback, of course, is that the study resolution gets more crude as the distance from the transmitter increases simply because the radials are getting farther apart.

The other approach is to define a study grid, construct terrain profiles to each point in the grid, perform a path loss calculation to each point, and then plot the results as a colored grid. There is a much greater computational burden associated with this approach since each of the extracted profiles can only be used to find the path loss at one point (in general). Also, recursive techniques cannot be used to accelerate the rate at which path loss results are obtained.

If a hypothetical study area with a 50 km radius is considered, and the radial line approach is used with 1 degree radial spacings and 0.1 km point spacings

along the radials, a total of 180,000 known path loss calculation points will result. If an arbitrary random point is chosen within the 50 km radius, the worst case distance difference between this point and a point where a path loss calculation has been done occurs at the end of the radials where they're farthest apart. This distance = $50.0 \times \sin(1.0 \text{ degree})/2.0$, or 0.43 km. If the total study area is considered with an area of 7,853 square kilometers, the average area represented by each known path loss calculation point is 0.0436 square kilometers.

With the fixed study grid, to achieve the same worst case distance error as the radial line study, the grid point spacing would be set at 0.86 km. With the 50 km radius, the number of grid points is about 10,617, so 10,617 terrain profiles with an average length of 25 km are required. This compares with the radial line case where only 360 radials required, each with a length of 50 km. This is a substantially greater computational burden for the fixed grid case. Moreover, when the total study is considered, each known path loss calculation point represents on average 0.739 square kilometers for the fixed grid, more than 16 times greater than the 0.0436 square kilometers for the radial line study. The average area a known point must represent is directly related to the amount of distance error which exists between an arbitrary random point chosen in the study area and the nearest known path loss calculation point.

While it is true the resolution of the radial line approach is concentrated near the transmitter, even with equivalent worst error conditions at the end of the radials as in the example above, the fixed grid approach is still inferior from a computational viewpoint. The radial line approach is thus preferred for propagation studies, and is widely used in commercially-available propagation software products.

3.0 DTEM Accuracy For Propagation Modeling

Propagation models use a variety of information from DTEM's to calculate path loss. For empirical models, such as the CCIR and FCC propagation curves, or the Okumura (Hata) model, usually only antenna height above average terrain (HAAT) and sometimes delta H (inter-decile terrain variation), is used. Models which primarily rely on average elevations or some other general terrain statistic, are fairly insensitive to DTEM accuracy. For example, calculated HAAT values from the 30 arc second and 3 arc second terrain databases covering the U.S. are typically within a

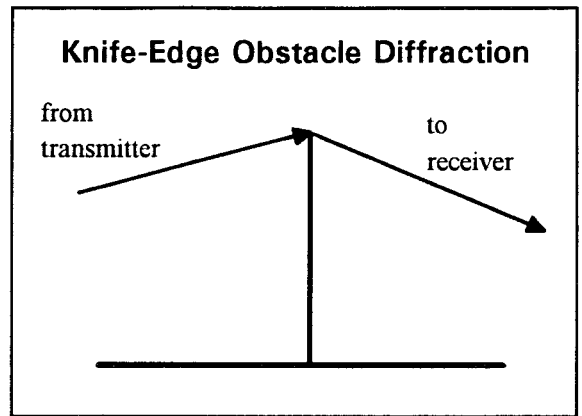


Figure 1 - Knife-edge obstacle diffraction.

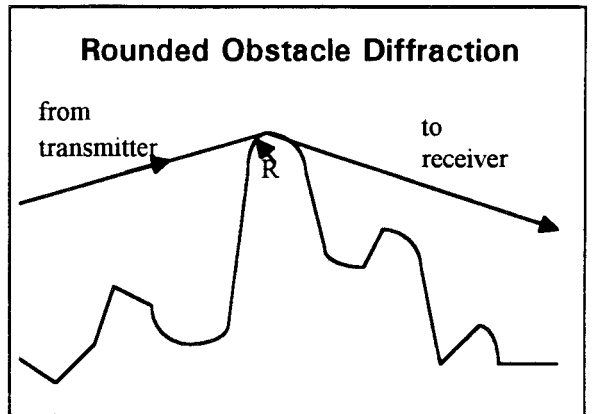


Figure 2 - Rounded obstacle diffraction.

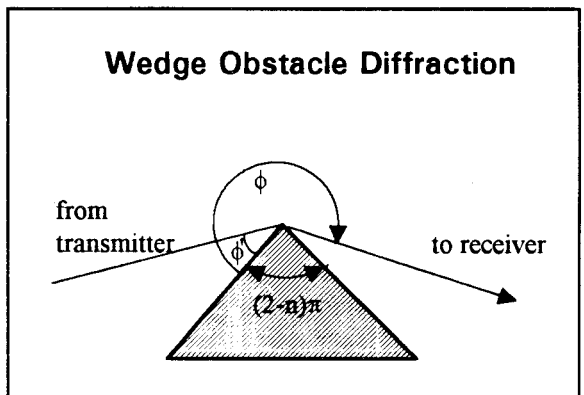


Figure 3 - Wedge obstacle diffraction.

few percent of each other despite the fact that the 3 arc second database has 10 times the horizontal resolution.

While these empirical propagation models require limited DTEM accuracy, because of this same insensitivity to terrain, these models can give seriously inaccurate path loss predictions when the terrain along the path departs widely from the average values.

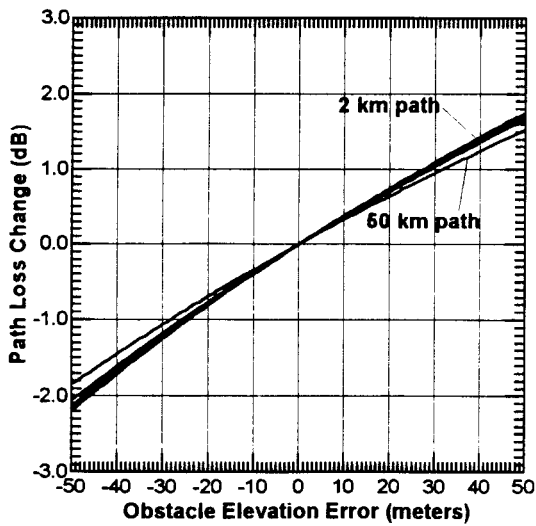


Figure 4 - Knife edge path loss change.

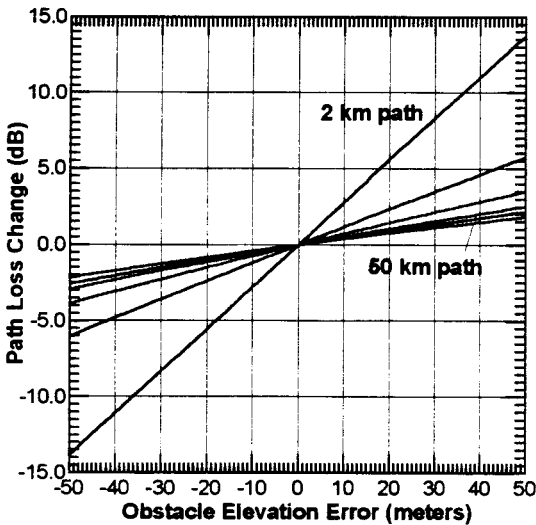


Figure 5 - Rounded edge path loss change.

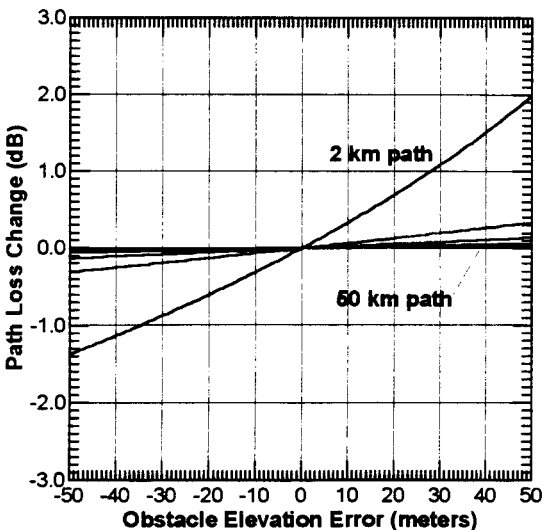


Figure 6 - Wedge path loss change.

Therefore, these models cannot be regarded as location-specific propagation models.

Location-specific propagation models use diffraction and reflection calculations of some type along with the actual x,y,z location of terrain features on the path between the transmitter and receiver. The question to be addressed here is what level of error can be tolerated in the x,y,z position of a terrain obstacle before the calculated path loss changes by a significant amount, say 1 or 2 dB? To examine this issue, calculations were done with three different terrain obstacle models - a knife edge, a "rounded" edge, and a lossy dielectric wedge. These obstacle models are shown in Figures 1, 2 and 3. These obstacle models are typical of those found in commonly-used propagation models, such as TIREM, Longley-Rice, JRC, etc., although each model may use different methods to combine losses due to multiple obstacles.

For each of the three obstacle models, a selection of path geometries were tested using path lengths of 2, 5, 10, 20, 30 and 50 kilometers. In each case a single isolated obstacle was positioned in the center of the path with the rest of the path elevations set to zero. The effective earth radius (k factor) was set at $4/3$. In each case the "correct" obstacle height was set at 250 meters, so as path length increased, the radio path bending angle over the obstacle became increasingly shallow. The transmit antenna elevation was set to 50 meters and the receiver antenna elevation was set to 3 meters above the zero elevation plane. The frequency was set to 500 MHz and vertical polarization was assumed.

For knife edge and rounded obstacle diffraction, the path loss was computed using the formulas in [3]. These are simple and efficient algorithms which were developed by curve-fitting the Fresnel diffraction loss curve in the shadow region. These equations do not apply outside the shadow region. The radius of the rounded obstacle was set at 100 meters.

For the wedge obstacle loss, the formulas found in [4] were used. A conductivity of 15 mS/m and a relative permittivity of 15 were used for the wedge material constants, values which are typical for the earth. The local wedge face roughness was set to 0.5 meters. In propagation models using wedge obstacles, the interior angle of the wedge is usually calculated using the terrain elevations on either side of the wedge center. A hill with gentle slopes would be represented by a wedge with a large interior angle, while a mountain peak or cliff might have a relatively small interior angle. For the studies done here, the interior angle was set at 140 degrees.

For each obstacle model type, and each path geometry, the obstacle loss was computed as the obstacle elevation was varied away from the "correct" value of 250 meters. These elevation variations, then, simulate DTEM elevation errors. The results of the studies are shown in Figures 4, 5, and 6 for the knife edge, rounded edge, and wedge obstacles, respectively. Note that the dB path loss scale for the rounded obstacle case in Figure 5 is different from the scale in Figure 4 and 6.

The results show that for knife edge and wedge obstacles, terrain elevation errors up to ± 50 meters can be tolerated without the calculated path loss changing by more than 2 dB. For rounded obstacles, the path loss changes are greater, but for ± 20 meter errors on all but the shortest path, the path loss changes are still within about ± 2 dB.

Similar studies were done with the nominal "correct" obstacle height set to 100 meters, such that the ± 50 meter error was a greater percentage of the total obstacle height. The path loss changes were greater but still within the 2 dB range for elevation errors of ± 15 meters. The results for the knife edge case are shown in Figure 7. The "kinks" in some curves are due to the transition from one equation to another from the knife edge diffraction loss curve fits in [3].

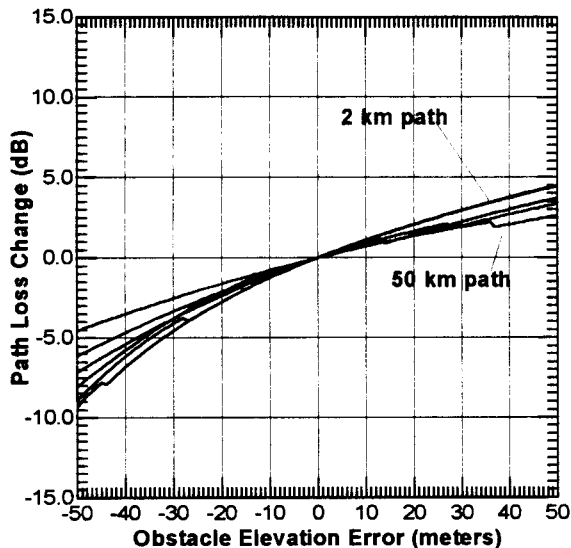


Figure 7 - Knife edge path loss change. Nominal "correct" obstacle height = 100 meters.

Additional studies were also done with the obstacle elevation held constant while the obstacle position along the path was varied by ± 100 meters. For all paths and obstacles, the resulting path loss changes were all less than about 1.5 dB. For the knife edge and wedge cases, the losses over this lateral error range were less than 0.5 dB.

Of course, these studies only consider obstructed paths and the relative path loss changes. A more dramatic change will occur when the elevation error results in the receive point making a transition from the line-of-sight to the shadowed region. Very small path elevation errors could cause this transition, and the resulting change in path loss will depend on the frequency and Fresnel zone radius. At 0.6 Fresnel zone clearance, the obstacle loss is 0 dB and increases to 6 dB when the path just grazes over the top of the obstacle.

4.0 Conclusions

A discussion of DTEM database retrieval techniques and required DTEM accuracy for effective use in propagation models has been presented. The following conclusions can be drawn from this discussion:

1. Grid format DTEM's using geographical latitude-longitude references are preferable to linear x,y or local grid referenced DTEM's.
2. Radial line-based propagation studies are computationally more efficient than fixed grid studies for equivalent study resolution.
3. DTEM elevation errors on the order of 25 meters (depending on absolute obstacle height and obstacle model) can be tolerated before typical calculated path loss changes by more than about 2 dB.

5.0 References

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