The Effect of Digital Elevation Model Resolution on Wave Propagation Predictions at 24Ghz

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Scott M. Rose

(Abstract)

Digital Elevation Models (DEMs) are computer-generated representations of the earth's surface. These surfaces can be used to predicted Line-of-Sight (LOS) radio propagation. DEM resolution can affect the results of this prediction. This study examines the effect of DEM resolution on accuracy by comparing varied resolution terrain data for a portion of Blacksburg, Virginia using the prediction of ESRI's ArcView® viewshed algorithm. Results show that resolutions between one-meter and thirty-meters have little effect on the aggregate accuracy of the viewshed.

Acknowledgements

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Chapter 1: Introduction and Background

1.1. Introduction

Visibility algorithms, both line-of-sight (LOS) and viewshed, applied to high-resolution Digital Elevation Model (DEM) data can be used to predict high-frequency radio signal coverage (I-cubed, 2001). Although lower-resolution DEM data might yield satisfactory results, there is no mention of a suggested resolution parameter in the literature. There is freely available data from the United States Geological Survey (USGS) at 30-meter resolution. The purpose of this study is to determine how DEM resolution affects the accuracy of a viewshed algorithm for radio propagation in both urban and rural settings.

The viewsheds for this study have been created using one of the more popular desktop geographic information systems (GIS) programs, Environmental Systems Research Institute's (ESRI) ArcView GIS®. The study will compare viewsheds calculated at resolutions of 1, 5, 10, 15, 20, 25, and 30 meters (both with and without building heights) as well as from the publicly available USGS 30 meter DEM to determine what effect resolution might have on propagation prediction accuracy. All data sets contain some degree of error, but it is impossible to determine where individual errors are located.

The three main components of this study are intervisibility, DEMs, and the properties of the 24 GHz radio wave. Information on each is provided below.

1.2. Radio Frequency

The 28 to 32 GHz radio frequencies have been designated as the local multipoint distribution service (LMDS). The LMDS' "A Block" bandwidth of 1150 MHz is the widest ever allocated by the FCC. This large bandwidth makes it an ideal medium for broadband-wireless Internet access and many other applications as well; however, signal quality can be significantly degraded or blocked by natural and man-made obstructions due to this band's relatively short wavelength. It is for this reason that a high-frequency signal was chosen to conduct this study.

The frequency used in this study is 24 GHz, which is close to the LMDS frequency and also a LOS frequency. This means that, according to theory, if you can see one point from another visually (up to a certain distance) then the 24 GHz signal will be received at that point with little or no signal loss. Conversely, if a point cannot be seen from another point, then very little or no signal will reach the receiver (barring any reflection from smooth surfaces).

1.3 Visibility

There is a simple question that can be asked using a viewshed or point to multipoint analysis: What can be seen from the observer location? For point-to-point applications the question becomes: Can the target be seen from the observer (Figure 1)?

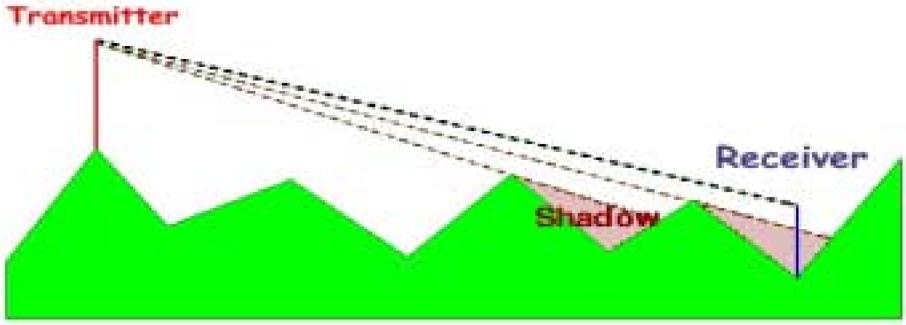


Figure 1-1. Example of Intervisibility.

Since this study uses multipoint (transmission from one point to cover an area) algorithms, signal coverage is defined as the area which can be "seen" from a single transmission source. An example of a multipoint coverage area is shaded green (Figure 1-2).

Figure 1-2 Viewshed Example

1.4 Digital Elevation Model (USGS)

Each 7.5-minute unit of DEM coverage (based on the 7.5-minute quadrangle) consists of a regular array of elevations referenced horizontally in the UTM projection coordinate system. For the Blacksburg study area, elevation units are in meters relative to the National Geodetic Vertical Datum of 1929 (NGVD 29).

A DEM is a regular grid of spot-elevation points spaced at regular intervals (Figure 1-3). According to the USGS, spot elevations are points with a measured vertical position of less than a third order accuracy, measured relative to a reference datum.

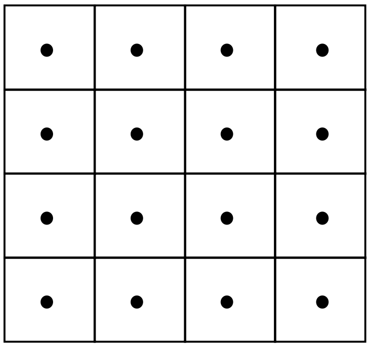


Figure 1-3. Spot elevation points

Accuracy is a function of the source, spatial resolution (cell size), and method of creation. A legitimate DEM cannot be created with a resolution higher than its source's resolution. Resolution is the size of each individual cell or grid.

In most studies a higher resolution DEM is considered advantageous because there is typically more data with a higher degree of accuracy. There are drawbacks to a higher resolution DEM. For example, the better the resolution of a DEM, the larger the file size – and in many cases the file size can be enormous. This, in turn, logarithmically increases the time necessary to run a viewshed algorithm.

The USGS (United States Geological Survey) 30-meter resolution DEMs were created using either digitized contour overlays or scanned National Aerial Photography Program photographs. Four different processes have been used to generate DEMs.

- The Gestalt Photo Mapper II (GPM2) is an automated photogrammetric system designed to produce orthophotos, digital terrain data, and contours in subunits known as patches.

- Manual profiling from photogrammetric stereomodels uses stereoplotters equipped with three-axis electronic digital profile recording modules for scanning stereomodels along successive terrain profiles. High-altitude aerial photographs are used as source material.
- Elevations are recorded by stereomodel digitizing of contours, in which digital contours are acquired on stereoplotters equipped with three-axis digital recording modules. The contours were assigned elevation values (attributes) during the acquisition phase. The contour data were processed into profile lines, and the elevation matrix was computed at a 30-m spacing using a bilinear interpolation.
- Interpolation from digital line graph (DLG) hypsographic and hydrographic data. All DEM data now being generated use this process. (USGS Data User Guide, 2001 & USGS Data User Guide, 1993).

The process involved with the creation of the Blacksburg DEM was the Gestalt Photo Mapper II. "The GPM2 (now discontinued) was an automated photogrammetric system designed to produce ortho--photographs, digital terrain data, and contours. An electronic image correlation component of the GPM2 measured the parallax of 2,444 points within each 9- x 8-mm area of a photogrammetric stereomodel. Of these 2,444 correlated points, subunits of 576, 1,024, or 1,600 points were collected for inclusion in the elevation model. These subunits were called patches, and the patch size was selected to accommodate various terrain conditions. The horizontal (x and y) spacing of the elevation points within each patch was approximately 182 mm at photographic scale (equivalent to a ground distance of approximately 47 ft when using photographs at

1:80,000 scale). Each of the two NHAP stereomodels used to cover a standard 7.5-minute quadrangle contained over 500,000 correlated points; these were regridded to form a DEM in the standard format. Before discontinuance, approximately 15,000 DEMs were added to the NDCDB using this autocorrelation system" (USGS Data User Guide, 1993).

According to the USGS "The method of determining accuracy of DEM data involves computation of the root-mean-square error (RMSE) for linearly interpolated elevations in the DEM compared to corresponding true elevations from the published maps. Test points are well distributed and representative of the terrain. Collection of test point data and comparison of the DEM to the quadrangle hypsography are conducted by USGS quality-control groups" (USGS Data User Guide http://edc.usgs.gov/glis/hyper/guide/7_min_dem).

"The accuracy of DEM data depends on the source and resolution of the data samples. DEM data accuracy is derived by comparing linear interpolation elevations in the DEM with corresponding map location elevations and computing the statistical standard deviation or root-mean-square error (RMSE). The RMSE is used to describe the DEM accuracy. For 7.5-minute DEM's derived from a photogrammetric source, 90 percent have a vertical accuracy of 7-meter RMSE or better and 10 percent are in the 8- to 15-meter range. For 7.5- and 15-minute DEM's derived from vector or DLG hypsographic and hydrographic source data, an RMSE of one-half of a contour interval or better is required" (USGS GeoData Digital Elevation Models Fact Sheet, 2000).

1.5. Digital Elevation Model (High Resolution)

The campus elevation and physical plant data was compiled by 3DI, LLC (http://www.3dillc.com/). The company literature outlines that process as follows:

1. After we received the photography, we prepped and the pugged (Drilled holes in the diapositives) in order to derive plate coordinates to run the aerial triangulation. The prepping process involved locating the existing control that was laid by a survey crew and picking three additional points down the center of each photograph. After the points were picked, each flight line was tied together and finally pugged.
2. Once the prepping and purging were finished, each model was set up on an analytical stereo instrument and plate coordinates were read. When the readings were completed the plate coordinates where adjusted using JFk triangulation software to get the final coordinates used in the mapping.
3. After completion of the triangulation the models were set back up in the instrument and the data was captured using Vrone mapping software. A photogrammetric technician then captured lines, symbols, etc.
4. Once the data is compiled into individual digital files the individual files are merged into one dataset which is then edited for accuracy and clarity.
5. Next contours are run on the entire file. The contours are created by using software that creates a triangulated irregular network from the linework and points that were gathered *on the ground*. Once the triangles are created contours are interpolated throughout the triangulated network.
6. Once the contours are created sheet neatlines are placed.
7. Contours and other data such as sidewalks, driveways, steps, etc. are removed from buildings.

8. Contour text, spot heights, and additional text for clarity was added and a final edit was done.
9. The data was then cut into individual sheets and sheet borders and grids were added. The sheets were then plotted at map scale.
10. The final step was to translate the data into AutoCAD and place the data on CD (3DI, LLC).

This process assures that accuracy was based off of National Map Standards and the elevation data used to create the DEM was accurate to within half of the contour interval (1 foot). This is essential to the accuracy of the study.

All of these factors, visibility, properties of the LMDS frequency, and DEM accuracy are the critical factors for this study. Without some understanding each of these issues, a thorough study could not be completed. The introduction demonstrated here gives ample background for this study.

Chapter 2 – Literature Review

2.1. Literature Review

In reviewing the literature for this study it was surprising to find that little work has been done regarding DEM resolution and propagation viewshed analysis. There has been research regarding varying viewshed algorithms, DEM resolution and accuracy regarding terrain representation, slope, aspect, and elevation but never research addressing the impact of resolution on viewsheds.

Within these studies though there is some very relevant material. Jay Gao, from the Department of Geography, at the University of Auckland, examined resolution and accuracy of terrain representation by grid DEMs at a micro-scale. He examined the impact DEM resolution on the accuracy of the gradient. Using three different DEMs with differing terrain types, the "accuracy (RMSE) of the DEMs was regressed against contour density and DEM resolution at six resolution levels." The resolutions were 20, 30, 40, 50, and 60 meters. These DEMs were resampled from a 10 meter DEM to keep any interpolation errors constant in all of the DEMs. "The accuracy of terrain representation was evaluated against root-mean-square error (RMSE) of elevational residuals at 200 randomly selected check points" (Gao, pg. 202, 1997).

The results revealed that "representation accuracy decreases moderately at an intermediate resolution, but sharply at coarse resolutions for all three terrain types"(Gao, pg. 210, 1997). These results could suggest that any study using DEMs with varying resolution would result in the same results.

The important points to focus on are: as DEM resolution decreased (larger cells), there was less accuracy and it dramatically decreased at both higher and very coarse resolutions while only gradually decreasing in the middle resolutions used in his study. Both of these points may be issues on any DEM resolution study and therefore pertinent to this study. Also, Gao's methods of creating the DEMs by resampling from one high resolution and of creating the DEM from one single source were copied in order to keep the error about equal in both amount and locations.

Another study conducted by Kang-tsung Chang and Bor-wen Tsai on the effect of DEM resolution on slope and aspect mapping shows resolution and its effect on a different type of measure. The experiment used five resolutions ranging from eight meters to eighty meters.

The goal of the study was to find out not only if better resolution DEMs improved slope and aspect data, but also how much improvement could be expected. Using ArcInfo to run the computations, Chang and Tsai tested two methods of classification for slope and aspect. First, a classification scheme of grouping slope values into: less than 5 %, 5-15%, 15-30%, 30-40%, 40-55%, and greater than 55%. The aspect values followed the eight principal compass directions (Chang & Tsai, pg 69-71).

The second study, more related to this study, used absolute values when testing rather than grouped values. An interesting side note is how the DEM was created because the same process used by Chang and Tsai is employed by this (viewshed) study as well.

The results of the study resembled Gao's in that as resolution decreased (cell size became larger), the accuracy of slope and aspect decreased. It also showed that in areas of steep elevation change, slope was affected much more than in areas of relatively little elevation change.

This fact may be useful in this study as well because of the steep elevation changes where buildings are located. While the Chang-Tsai study did not have a DEM with such extreme elevation changes, it may represent a typical effect on steep slopes.

Unfortunately, ESRI does not disclose the actual algorithm used in ArcView's® viewshed model. We can, however, look at Peter Fisher's study on "Algorithm and Implementation Uncertainty in Viewshed Analysis" in which he compares viewshed results from several GIS software packages.

The purpose of his study is to "highlight three issues: the need for standards and/or empirical benchmark datasets for GIS functions; the desirability of publication of algorithms used in GIS operations; and the fallacy of the binary representation of a complex GIS product such as the viewshed."

Two of the three main points that Fisher touches on are extremely pertinent to this study. Not knowing the algorithm used by ArcView limits any discussion of error. Also, the binary representation that ArcView uses does not allow for any points that "may be" useful in real world LMDS applications, it considers them either visible or not visible.

Fisher also discusses and analyses how different GIS software with the same function, on the same data, will derive different results. These differences can be large. Unfortunately, ArcView was not among the tested software. It is important to note that Fisher's study did include ArcInfo®, another product from ESRI, and it may use the same viewshed algorithm in both pieces of software. However, because we do not know for certain that this is the case, it will be treated as a separate algorithm.

Fisher's study conveys the issue that this study only examines ESRI's ArcView® Viewshed algorithm and that using another GIS software package may derive different results. Also he discusses the binary (Yes/No) results of GIS functions and how they do not relate well with many real world functions, like predicting radio signal coverage.

Another important issue with this study regards the validity of the study. For example: Do wireless companies pay for and use high resolution DEM data? There are several companies that specialize in this very industry. One such example is I-cubed LLC (http://www.i3.com/).

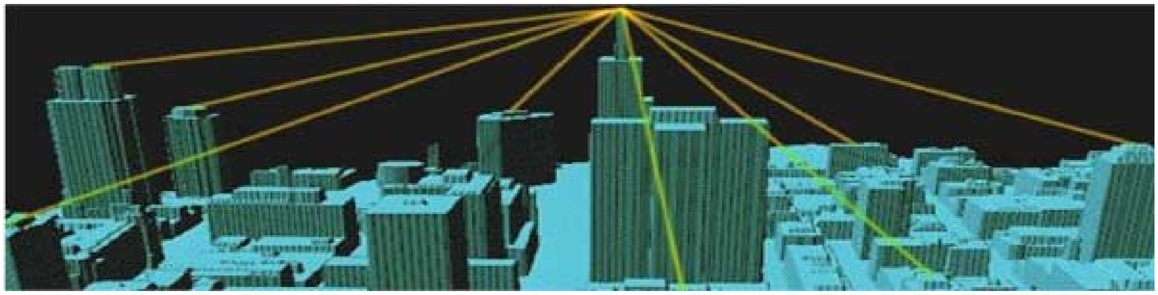


Figure 2.1 (I-cubed example)

Its mission statement reads: "I-cubed is a geo-processing service organization that offers complete business solutions based on information and geodata derived from air photos, satellite imagery and other sources of geographic information. Its impressive client base includes many of the world's largest wireless telecommunications companies, radio-frequency tool providers, and industry leaders in land and natural resource management, agriculture government organizations, and visual simulation applications" (http://www.i3.com/corporate/about.htm).

Each study above helped define how this study would be conducted. In Gao's study, it is understood that as resolution increased, accuracy increased. Gao's study relates to this study because the purpose is to find out how resolution affects accuracy in both his study and this study. Also, portions of his methods were used in planning for this study.

Chang and Tsai's study examined the way in which DEM resolution affected slope and aspect. Their study found, just as did Gao, that as resolution increased, accuracy increased. Also, the fact that they found that slope was affected more in steep elevation changes is extremely pertinent to this study because of the steep slopes at the edges of buildings.

In Fisher's study, it was important to note that ArcView® is only one of many software systems available that will run a viewshed algorithm and will derive different results. It touches on issues that affect this study such as the desirability of publication of algorithms used in GIS operations.

The purpose of discussing I-cubed was to introduce the importance of the study. The company can generate DEM resolution as high as a few centimeters with accuracy similar to the accuracy in this study (viewshed).

There has been little published research in the specific area this paper examines – the effect of DEM resolution on viewsheds. The discussion above was the most pertinent information found.

Chapter 3: **Methods**

3.1. DEM Creation

The creation of two sets Digital Elevation Models (1, 5, 10, 15, 20, 25 & 30 meters) – (one set with buildings, one set without buildings) was critical in determining the effect resolution had on the accuracy of the viewshed. If the DEMs were inaccurately created the entire study would be flawed. Luckily our source data for the DEMs (except the USGS 30 meter) were available with accuracy to half a foot, which complies with National Map Standards.

Secondly, building data was added to the one set of DEMs are horizontally accurate to within the National Map Standards. The building heights were obtained both by triangulation and from the building's original architectural drawings. While many building tops have some slight elevation variation, it was not incorporated in this study due to time and cost limitations.

3.1.1 Computer Processes

The original file format was an AutoCAD file created using the processes described in Chapter 1. From the AutoCAD file the elevation contour lines and building outlines were extracted and imported into ESRI's ArcView 3.2®. In ArcView, the Spatial Analyst Extension was loaded and the contour lines were converted into a Triangulated Irregular Network (TIN) Figure 3.1. A TIN is a surface representation derived from points and breakline features. Each point has an x,y coordinate and a surface, or z-value. These points are connected by edges to form a set of nonoverlapping triangles used to represent the surface.

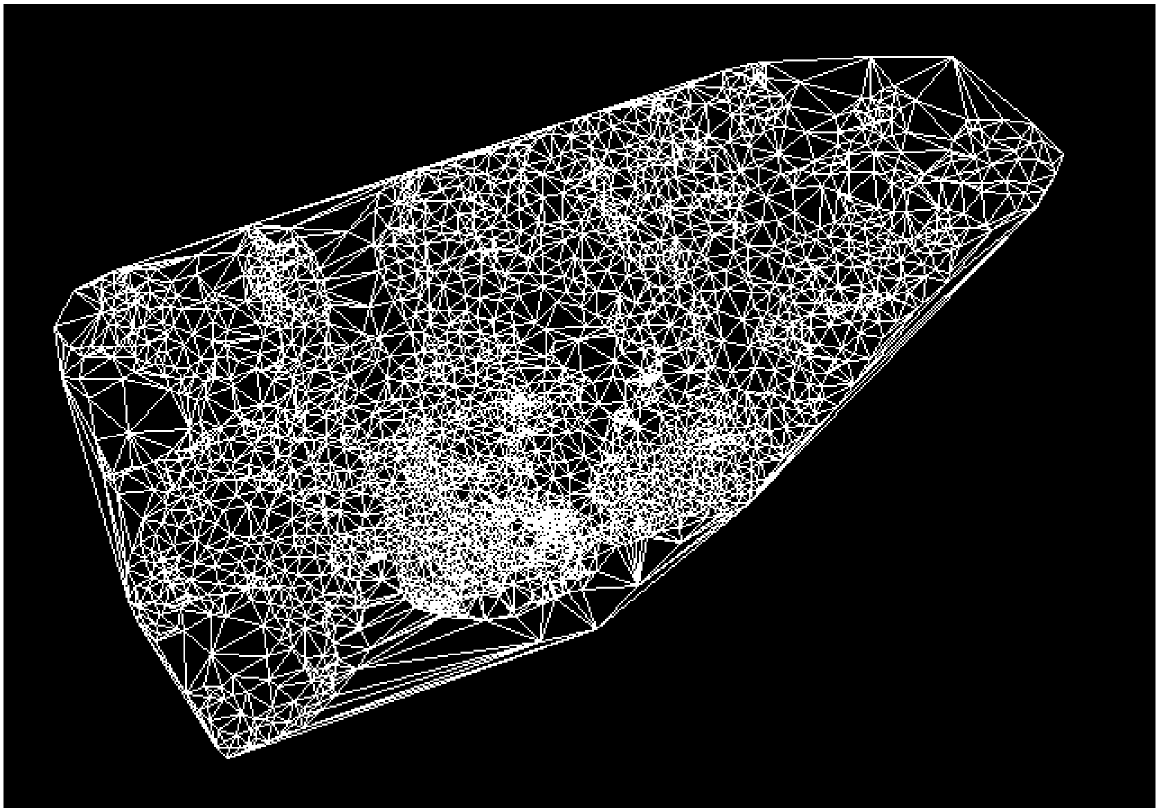


Figure 3.1 Example of a TIN

The reasoning for using a TIN rather than immediately converting to a grid or DEM is based on processing time. Initial attempts to create a 1-meter resolution DEM directly from the contour lines were abandoned because the process time required more than a week of CPU time on a Pentium II® - 450 MHz – 256MB RAM – Computer. The TIN alternative was discovered to significantly reduced computation time without reducing accuracy. This process took several hours rather than days. The next step was to convert from a TIN to a DEM.

In order to insure that the process of using TINs did not reduce accuracy, several DEMs were compared with the contour line values. The value for both the contour line and the DEM were obtained from the same location and the differences found were minute. Ten random cells were compared and found that the largest difference between the two was approximately 0.1 meters.

Once the 1-meter DEM was created, the 5, 10, 15, 20 & 25 meter DEMs were created by resampling. The 30-meter USGS DEM was simply downloaded from the internet (http://edcftp.cr.usgs.gov/pub/data/DEM/7.5min/B/blacksburg_VA/) and imported into ArcView®.

Also on the 1-meter DEM, the existing, real world features were added on top of it in order to get a real world (with buildings) model into the computer. This was done again using ArcView and ArcView's Spatial Analyst extension.

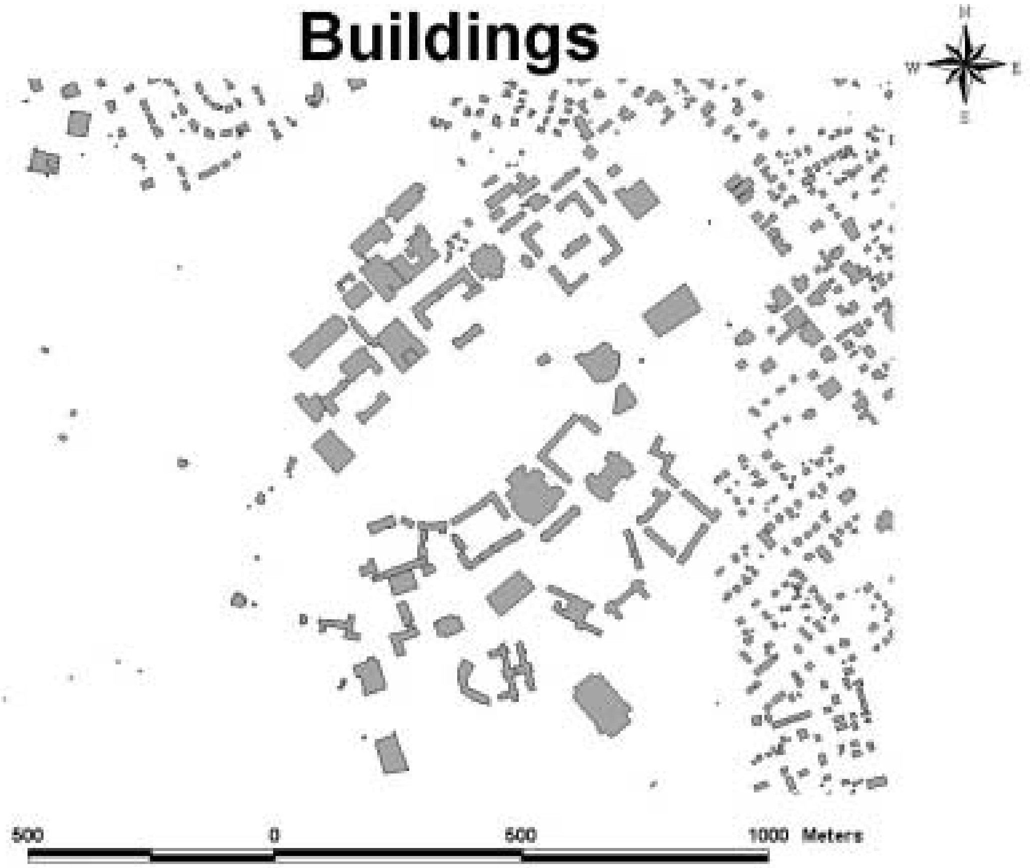


Figure 3.2 Example of Building Layer

First the AutoCAD building layer (Figure 3.2) was imported into ArcView shapefile format using ArcView. Then a field was added to the building attributes to record heights. Using the data obtained from measurements and the architectural drawings the correct height was entered for each object. Based on this field, the shapefile was then converted to a grid. This grid filled the cells in a building's outline with its height against a background of zero values.

In order to resolve the issue of having an uneven rooftop (simply placing a building with a constant height onto a DEM with uneven terrain would create an uneven, sloped rooftop), the building shapefile was used with the DEM to compute the average height of the ground within each building outline. This created a flat area on the terrain DEM onto which the building DEM would be placed giving a flat rooftop (Figure 3.3).

Figure 3.3 DEM showing flat rooftop elevations

Next the building grid was added to the elevation grid (DEM). This was accomplished by using ArcView's® Spatial Analyst extension and created a DEM with building height represented on it.

This process was performed on the one-meter DEM and on each lower resolution DEM that was created from it. These processes enabled this study to have an extremely accurate database (DEM, buildings) to test the accuracy of the viewshed as well as how resolution will affect the accuracy.

3.2. Field Data

In order to verify the results of the computer simulation, real world data was needed. As stated in the introduction, the campus of Virginia Tech was used for the sampling for the reason that it has both urban and rural characteristics.

A transmitter was placed at the southwest corner of the roof of Whittemore Hall at 42 meters above ground. The transmitter consisted of a power source, signal generator, a one-meter pole, and the antenna.

The signal frequency was 24.12 GHz and the antenna was a horn with a total horizontal directional beam of 50 degrees. This is very important because if you take measurements on the outer part of that 50-degree beam, the signal received will be lower. In order to prevent this effect, the points were taken only if they were within approximately 15 degrees from center in either direction, then the antenna rotated to cover a new portion of the study area.

The receiver consisted of an antenna, spectrum analyzer, GPS unit and a power source. The receiver was taken to just under one hundred regularly spaced sample points around the campus (Figure 3.3). Using the campus base map, navigating close to the regular grid that proposed was extremely simple.

Figure 3.4 Locations of Field Points Taken

At each point a signal measurement (in dB) was taken by aiming the receiver horn directly at the transmitter. The measurement was taken even if there was an obstruction. If no peak was visible (Figure 3.5), the horn was aimed at various potential reflection points and if a peak was visible a reflected measurement was taken. A peak is the highest noticeable point on a spectrum analyzer. Figure 3.5 is an example of a spectrum analyzer screen. Also at each point, the GPS unit was used to log the location.

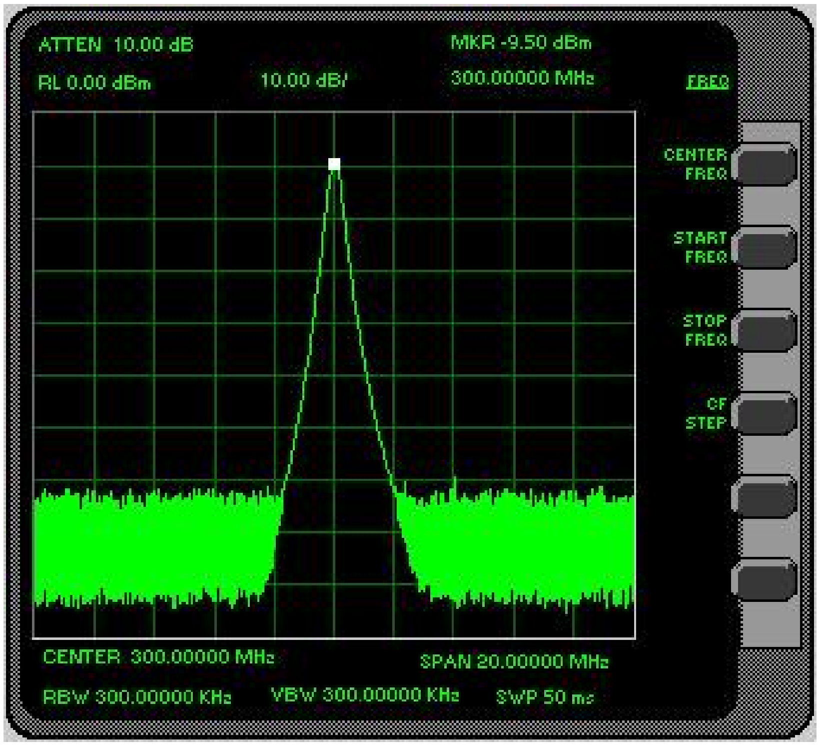


Figure 3.5 Example of Spectrum Analyzer Screen

The GPS points were located, and then the associated data was attached into a database file (.dbf) and loaded into ArcView. Using this location data, a point was mapped for each measurement taken. This completed the field data collection.

3.3. Study Area

The area being studied is located in Blacksburg, Virginia. The area is rather rural except for the campus, which has large building structures (Picture 3.1). This photo also shows the transmitter location on the southwest corner of Whittemore Hall.

Picture 3.1 Aerial View of Transmitter

The Building Heights used in this study range from 13 meters up to 126 meters. The terrain in the area, without the building heights ranges from 616 meters to 642 meters. Picture 3.2 below shows a larger area of the campus and is meant to give a visual impression of the study area.

Picture 3.2 Aerial Picture of Study Area

Chapter 4: **Discussion**

4.1. Field Data Interpretation

The most important aspect of this study is to understand how DEM resolution affects the accuracy of the viewshed. In order to do this, we also need to understand how well ArcView's® viewshed algorithm can predict LOS signal coverage compared to the field data gathered. The next step is to see how much better, if any, it predicts at higher-resolutions both with and without building heights added to the DEMs. Finally we want to see if there is a significant difference in the predictions using the high-resolution data with building heights versus the USGS thirty-meter resolution data (without building height data).

In order to answer these questions, the data from the field needed to be interpreted to see which points were obstructed and which ones were unobstructed. To determine whether or not a point was within "reasonable" limits to be considered unobstructed, Dr. Dennis Sweeney (Virginia Polytechnic Institute and State University, 2001) was consulted and asked what limit should be considered to determine this. He concluded that a recorded reading within 3 dB of the predicted value was great, within 6 dB good, and at 10 dB it was not very good. Using this statement, this study used a breaking point of within 6 dB as unobstructed, and more than 6 dB as obstructed.

The Friis formula was used to determine what reading we should have seen at the receiver barring any interference from buildings, vegetation, or other obstruction. The path loss formula calculates the amount of loss there is due to distance from the transmitter.

We compare this result with the actual field result and subtract the calculated power from the measured power to yield the excess loss. For the seventy-eight points used, a range of 0 to –64 Db was found. The method used to find the predicted value was as follows (Friis Formula):

Predicted Signal Strength = (Transmitter Power + Transmitter Antenna Gain – Path Loss – Miscellaneous Loss + Receiver Gain)

For example: (13dBm) + (12dB) – (120dB) – (3 dB) + (20 dB) = -78dBm

All but the Path Loss stayed constant. The path loss was determined by the calculation:

Path Loss = 20log((4π * distance in meters)/wavelength in meters))

For example (1 Km): 20log((4π * 1000)/.0124) = -120dB

4.2. Simulation Data Interpretation

Out of the seventy-eight points, seventeen were unobstructed (Figure 4.1).

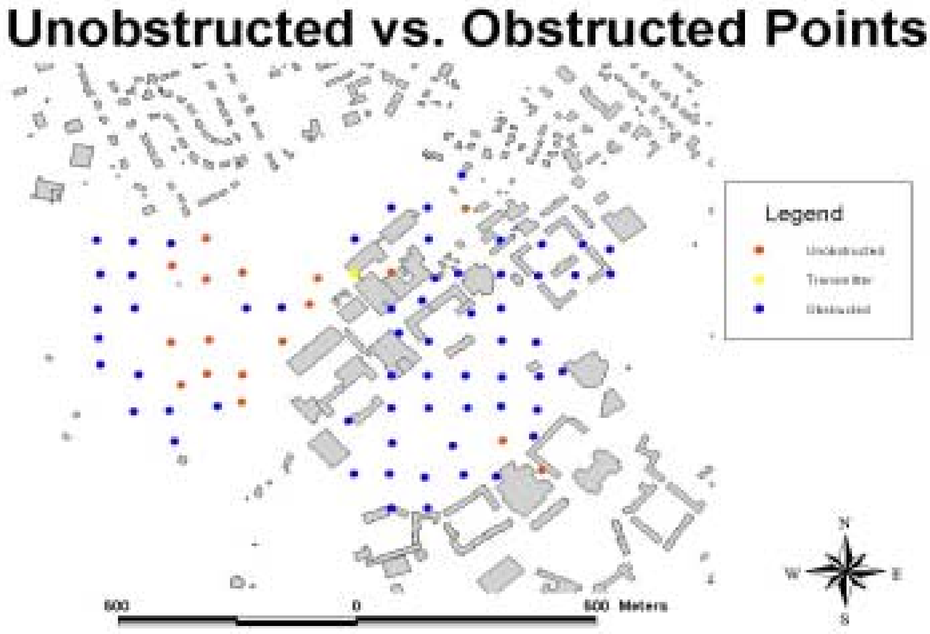


Figure 4.1 Shows points obstructed and unobstructed

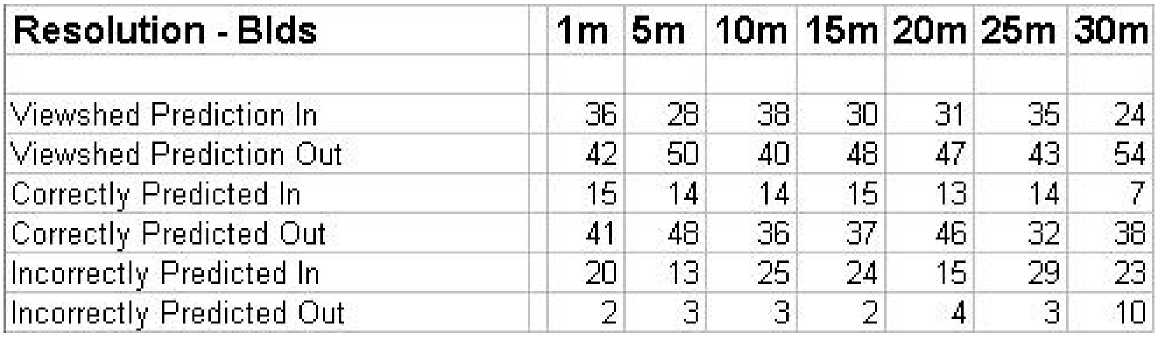
The majority of these points were in the area considered rural (no buildings). The reason for so few points is because of the major blockages of buildings and also significant pine vegetation in some areas.

The next phase was to examine the field results compared with the viewshed results from ArcView®. The viewshed was run on each resolution (1, 5, 10, 15, 20, 25, 30) from the single point (transmitter location) on the southwest corner of Whittemore Hall. The algorithm used by ArcView® has several settings that are customizable. These settings are the transmitter height, height of the receiving cells, upper limit of the vertical beam, lower limit of the vertical beam, horizontal limits, and the inner and outer radius.

The transmitter height was placed at one-meter above the height of the building (43 meters), representing the one-meter pole used in the study. The receiving cells were raised to almost one meter to represent the height of the receiving antenna. The upper and lower vertical and horizontal limits were left to default for the reason that these limits did not apply to this horn antenna. The outer limit was set to 2500 meters to be sure each point was within the viewshed analysis area. By limiting the radius, it reduces the computation time to only the area within the limits.

4.3. Total Results with Building Data

After running the viewshed for each resolution, the results were entered in to a spreadsheet (Table 4.1).



Resolution - Blds	1m	5m	10m	15m	20m	25m	30m
Viewshed Prediction In	36	28	38	30	31	35	24
Viewshed Prediction Out	42	50	40	48	47	43	54
Correctly Predicted In	15	14	14	15	13	14	7
Correctly Predicted Out	41	48	36	37	46	32	38
Incorrectly Predicted In	20	13	25	24	15	29	23
Incorrectly Predicted Out	2	3	3	2	4	3	10

Table 4.1 Total Results with Building Data

The category Viewshed Prediction In shows how many total points the viewshed calculated as unobstructed. Viewshed Prediction Out displays the number of points calculated as obstructed.

The next four categories compare the field data results to the viewshed algorithm results. The category Correctly Predicted In shows the number of points that were correctly predicted by the viewshed algorithm as unobstructed. Conversely, the category Correctly Predicted Out shows the number of points that were correctly predicted as obstructed. The next two categories show the number of points that are incorrectly predicted as unobstructed (Incorrectly Predicted In) and incorrectly predicted as obstructed (Incorrectly Predicted Out) by ArcView's® viewshed algorithm.

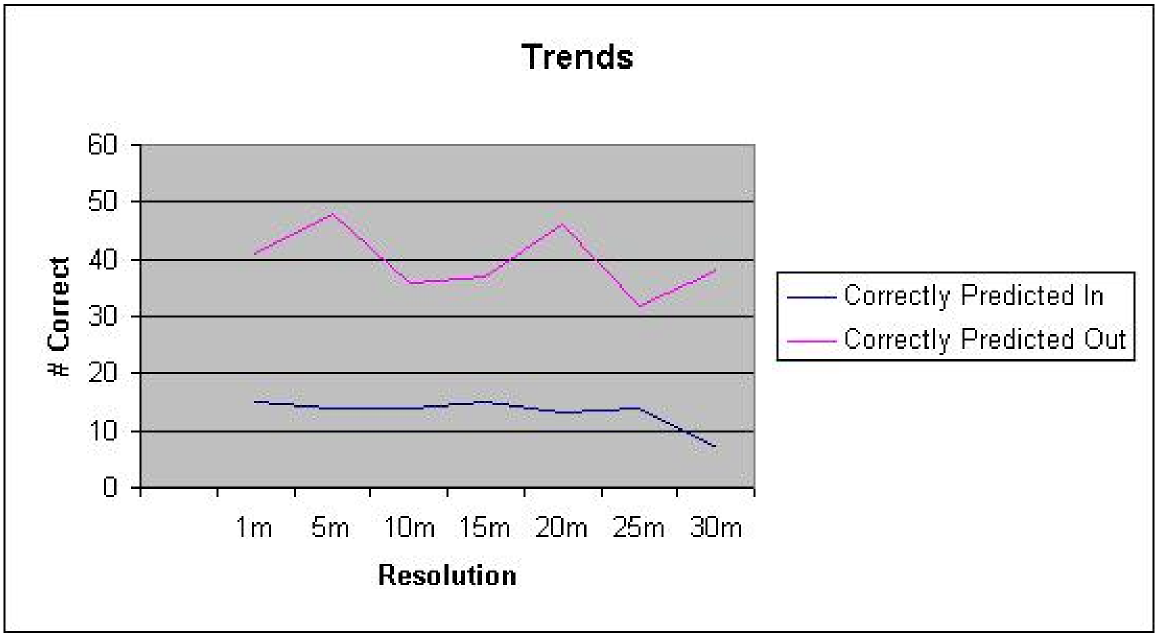


Figure 4.2 Correctly Predicted Points for the Total Area with Buildings

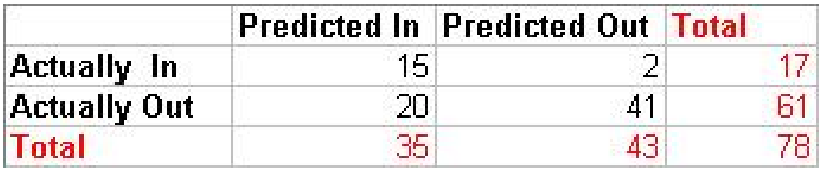
As can be seen by Table 4.1 and Figure 4.2, there is no great trend across the resolutions in the results of the study. Only a slight trend in the number of correctly predicted obstructed points suggests that as resolution gets worse, the predictions get worse. It seems that there is no noteworthy increase in the number of points correctly predicted as unobstructed. In fact, the one-meter DEM and the 25-meter DEM are almost identical. It does appear though; that the USGS 30 meter DEM does have more significant error with ten incorrectly predicted out verses a maximum of four in the other six DEM resolutions.

Khat Compared Significance					
1m &5m N	5m &10m Y	10m &15m N	15m &20m N	20m &25m Y	25m &30m Y
1m &10m N	5m &15m Y	10m &20m Y	15m &25m N	20m &30m Y	
1m &15m N	5m &20m N	10m &25m N	15m &30m Y		
1m &20m N	5m &25m Y	10m &30m Y			
1m &25m Y	5m &30m Y				
1m &30m Y					

Table 4.2 KHAT Significance Test for Total Results with Buildings

In each of the different sections a KHAT analysis was used to determine whether or not there is a significant difference between each DEM resolution result.

The KHAT "is a discrete multivariate technique used in accuracy assessment for statistically determining if one error matrix is significantly different than another" (Congalton, 49). An example of the KHAT error matrix is illustrated in Table 4.3.



	Predicted In	Predicted Out	Total
Actually In	15	2	17
Actually Out	20	41	61
Total	35	43	78

Table 4.3 Example of Input for KHAT

In Table 4.2, the KHAT analysis shows that there are few significant differences when moving from high-resolution data to low-resolution data (with buildings). There is however a significant difference between the 30-meter resolution and all other resolutions. The table illustrates that a DEM with a resolution as low as twenty-meters is just as useful as the one-meter DEM.

4.4. Urban Results With Buildings

Breaking the points down into urban and rural points can be useful. It will show if one area type is notably better for propagation prediction using the viewshed. First to be examined are the urban results. What constitutes an urban area for this study is any point that is or could be obstructed by a building or structure (Figure 4.3).

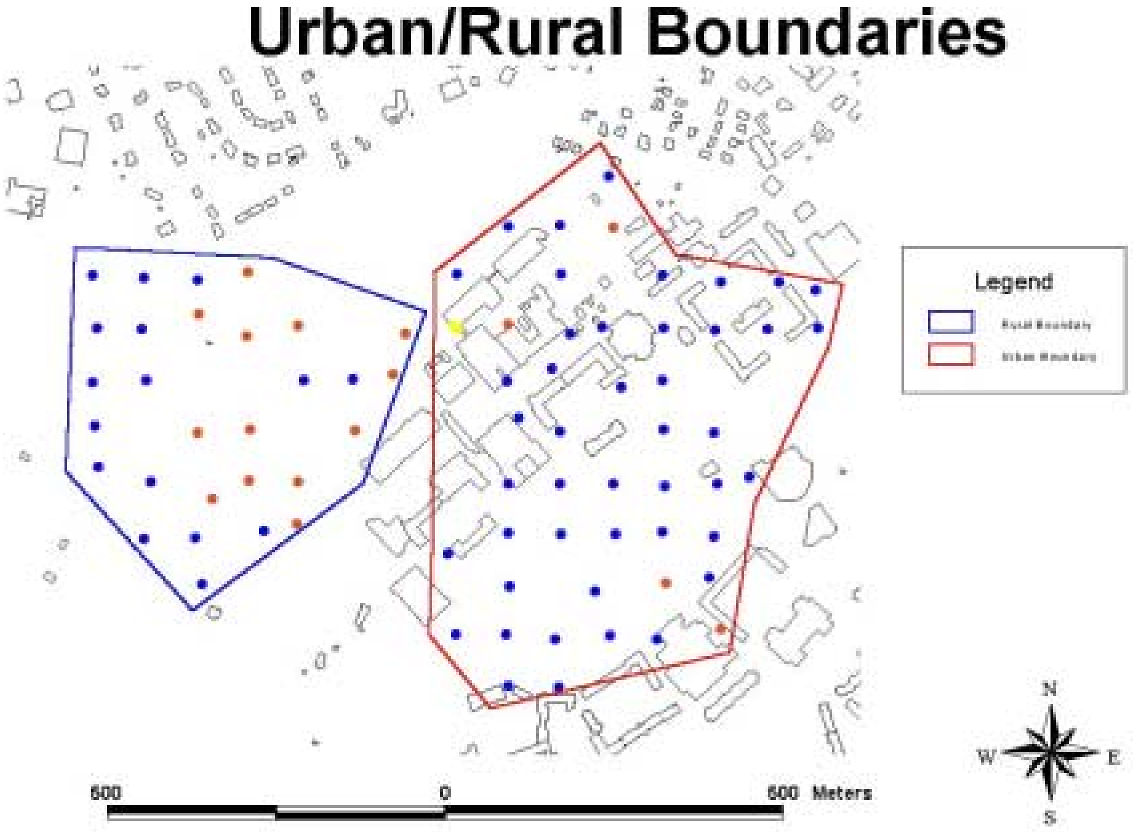


Figure 4.3 Urban and Rural Boundaries

Of the seventy-eight points taken, forty-nine of them were considered urban due to potential building obstruction.

The results of the urban area showed that only four of the forty-nine points were considered unobstructed in the field data while forty-five of them were obstructed. When compared to the viewshed results, the outcome is as shown in Table 4.4.

Urban - Resolution - Blds	1m	5m	10m	15m	20m	25m	30m
Viewshed Prediction In	6	3	10	10	12	14	14
Viewshed Prediction Out	43	46	40	39	37	35	35
Correctly Predicted In	2	2	1	2	1	1	2
Correctly Predicted Out	41	44	36	37	34	32	32
Incorrectly Predicted In	4	1	9	8	11	13	12
Incorrectly Predicted Out	2	2	3	2	3	3	2

Table 4.4 Urban results with building data

As shown in Figure 4.4, in the urban area there is a noticeable trend in the correctly predicted out or obstructed points. It also shows that there are no trends in the correctly predicted in data. This data set only varies between one and two. Overall the USGS thirty-meter data did not drastically reduce the accuracy of the data because it keeps very closely with the trend and it strikingly similar to the twenty-five meter data.

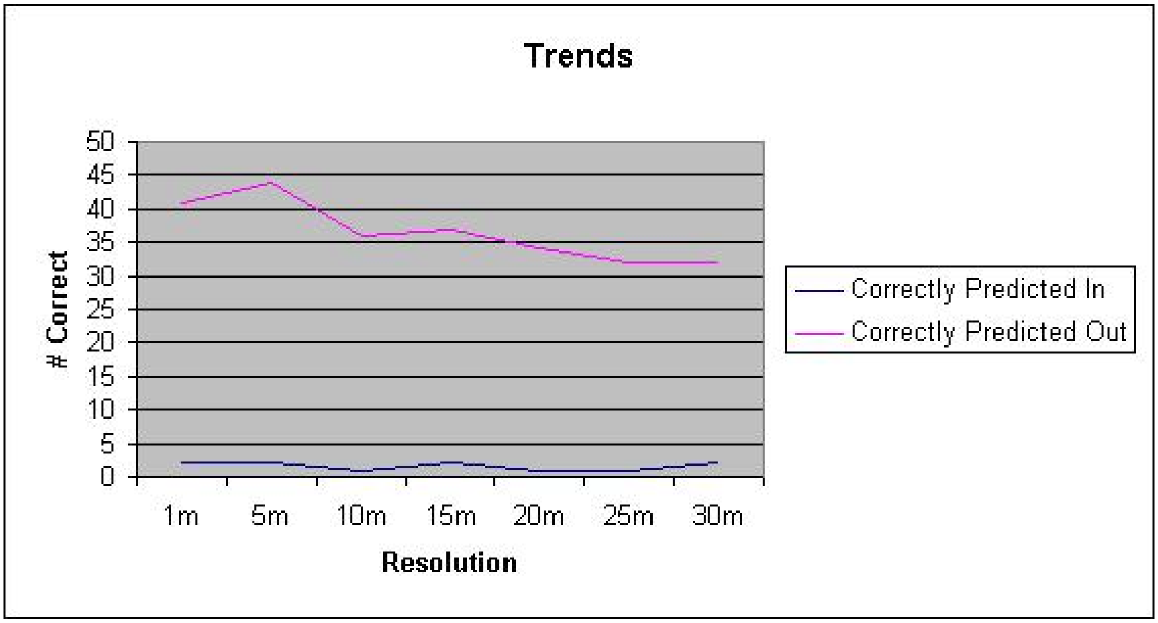


Figure 4.4 Correctly Predicted Points in Urban area with building data

Khat Compared Significance					
1m &5m N	5m &10m Y	10m &15m N	15m &20m N	20m &25m N	25m &30m N
1m &10m Y	5m &15m Y	10m &20m N	15m &25m N	20m &30m N	
1m &15m N	5m &20m Y	10m &25m N	15m &30m N		
1m &20m Y	5m &25m Y	10m &30m N			
1m &25m Y	5m &30m Y				
1m &30m N					

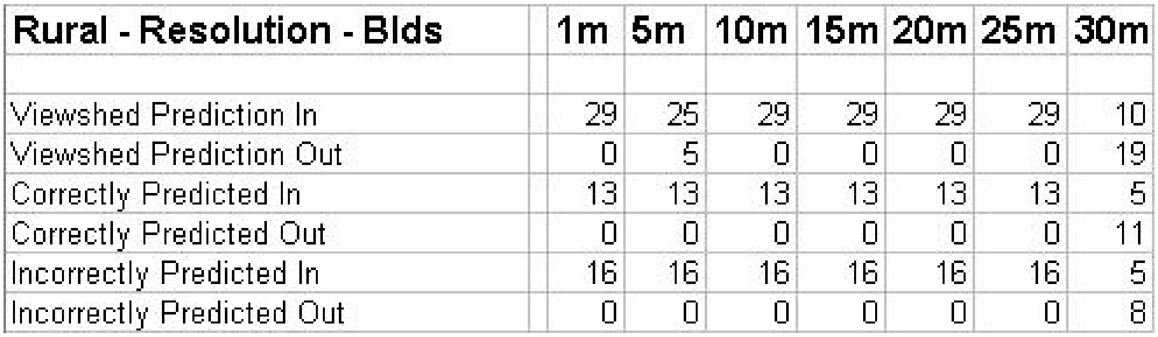
Table 4.5 KHAT Significance test for urban area with building data

When examining the urban results with buildings KHAT significance test (Table 4.5), it shows that there is no significant difference between the error matrix for a one-meter resolution DEM and the USGS thirty-meter resolution DEM. This is an extremely important finding because it shows that it is possible, in urban situations, to get similar results without paying the extra money for the high-resolution data.

4.5. Rural Results With Buildings

The rural area consisted of twenty-nine points. Of these twenty-nine points, the field study showed that thirteen points were unobstructed and sixteen were obstructed. The main obstruction in this area was an abundance of pine trees. This pine vegetation drastically reduced the received power at the receiving antenna.

The rural viewshed outcome is listed in Table 4.6.



Rural - Resolution - Blds	1m	5m	10m	15m	20m	25m	30m
Viewshed Prediction In	29	25	29	29	29	29	10
Viewshed Prediction Out	0	5	0	0	0	0	19
Correctly Predicted In	13	13	13	13	13	13	5
Correctly Predicted Out	0	0	0	0	0	0	11
Incorrectly Predicted In	16	16	16	16	16	16	5
Incorrectly Predicted Out	0	0	0	0	0	0	8

Table 4.6 Rural Results with building data

This spreadsheet clearly shows that in a rural area the higher resolution data may not be any better than the free data given by the USGS. In fact, in this study the USGS is as good and mostly better than the highly accurate data in every category listed (Figure 4.5). The total number of correctly predicted points is better in the USGS DEM; sixteen for USGS versus thirteen for the one-meter. The reasons for this could be endless, but a possible reason this is seen is because the error in the USGS DEM blocks more cells, in a sense, representing the vegetation lacking on the other. Again, there can be many reasons for this, to speculate on each would be of no value.

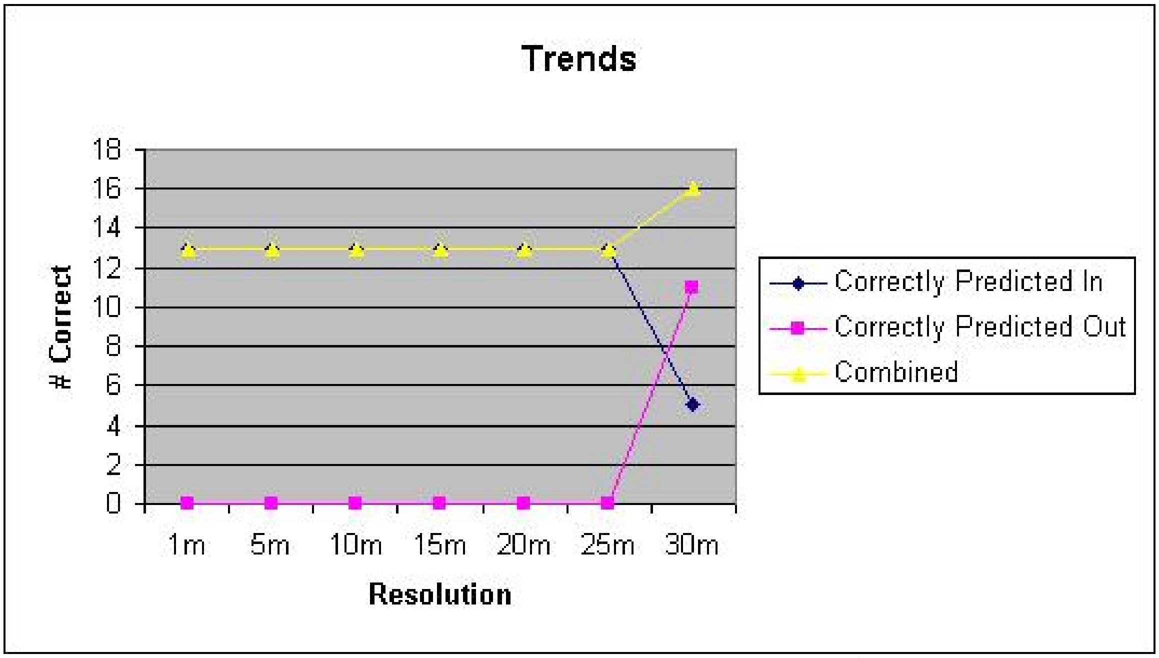


Figure 4.5 Correctly Predicted points for rural area with building data

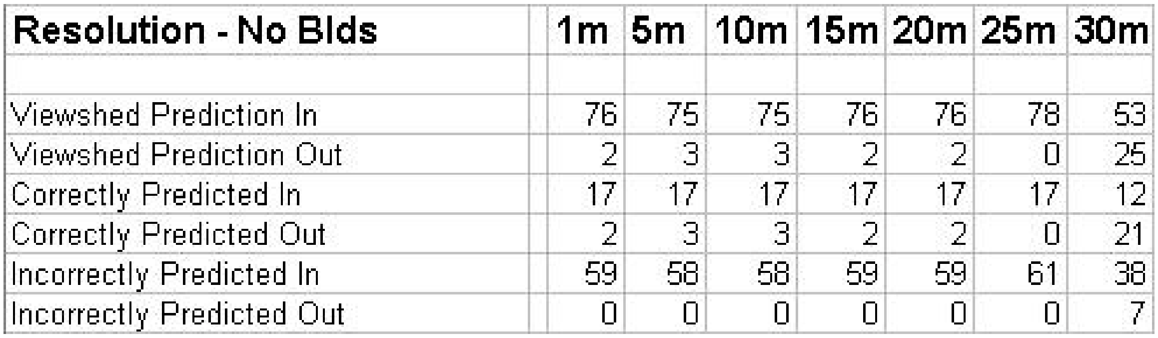
Khat Compared Significance					
1m &5m N	5m &10m N	10m &15m N	15m &20m N	20m &25m N	25m &30m N
1m &10m N	5m &15m N	10m &20m N	15m &25m N	20m &30m N	
1m &15m N	5m &20m N	10m &25m N	15m &30m N		
1m &20m N	5m &25m N	10m &30m N			
1m &25m N	5m &30m N				
1m &30m N					

Table 4.7 KHAT Significance Test for rural area with building data

According to Table 4.7, There is no significant difference whatsoever between the different resolutions. This result tells us that, for rural deployments of LMDS or other LOS radio systems, the free data from the USGS should be as good as purchasing high priced data (if it were even available). It also shows the importance that vegetation plays at these frequencies. Since water absorbs radio signal at these frequency, and water is found in the vegetation, its presence is extremely important.

4.6. Overall Results Without Buildings

In order to correctly compare the free data as it comes (without buildings) with the highly accurate data, a comparison of both without building heights was conducted as well. The results are shown in Table 4.8.



Resolution - No Blds	1m	5m	10m	15m	20m	25m	30m
Viewshed Prediction In	76	75	75	76	76	78	53
Viewshed Prediction Out	2	3	3	2	2	0	25
Correctly Predicted In	17	17	17	17	17	17	12
Correctly Predicted Out	2	3	3	2	2	0	21
Incorrectly Predicted In	59	58	58	59	59	61	38
Incorrectly Predicted Out	0	0	0	0	0	0	7

Table 4.8 Overall Results without building data

The results of this study were extremely surprising. The highly accurate data vastly over-predicted the points that were unobstructed. As shown here, the change in resolution had little effect on the results. The major difference was the source data. The USGS thirty-meter DEM predicted much better than the highly accurate data (Figure 4.6).

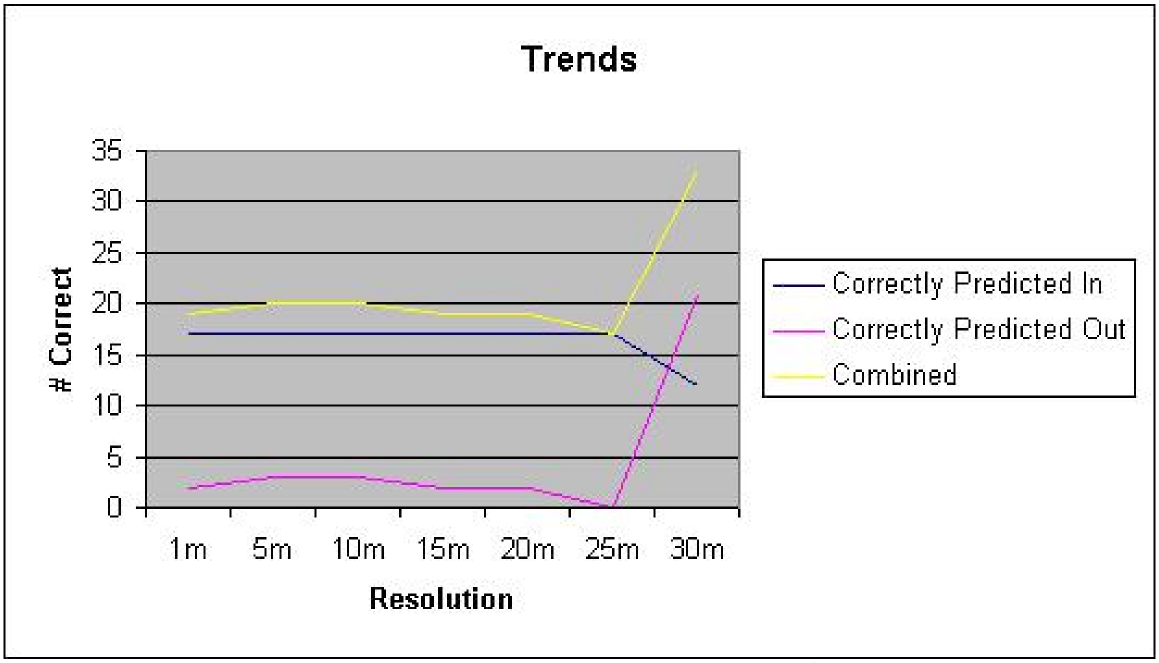
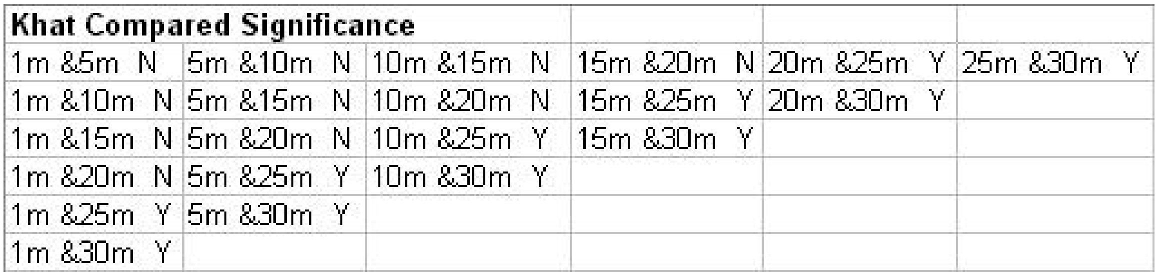


Figure 4.6 Correctly Predicted points for overall area without building data

Figure 4.6 shows the degree to which the USGS DEM produced better results. More interesting though, is that there was only a tiny variation in accuracy within the different resolutions of the highly accurate data. The reason for the over-prediction is obvious. Without using the known obstructions in the data, the height of the transmitter is high enough to "see" most of the study area. Also, once again vegetation was not included, which was a substantial “real world” obstruction particularly in the rural area.



Khat Compared Significance					
1m &5m N	5m &10m N	10m &15m N	15m &20m N	20m &25m Y	25m &30m Y
1m &10m N	5m &15m N	10m &20m N	15m &25m Y	20m &30m Y	
1m &15m N	5m &20m N	10m &25m Y	15m &30m Y		
1m &20m N	5m &25m Y	10m &30m Y			
1m &25m Y	5m &30m Y				
1m &30m Y					

Table 4.9 KHAT Significance test for overall area without building data

The KHAT test results (Table 4.9) reveals that there is a significant difference between the high-resolution and the low resolution. In this case the thirty-meter resolution DEM is more accurate and therefore it is significantly better than the costly high-resolution DEM.

4.7. Urban Results Without Buildings

This may be an extremely important aspect of the study for those that cannot or would prefer not to pay high dollar amounts for highly accurate data. Even in rural areas, a portion of the LMDS layout would likely include regions possessing urban characteristics. Table 4.10 below shows the result.

Urban - Resolution - No Blds		**1m**	**5m**	**10m**	**15m**	**20m**	**25m**	**30m**
Viewshed Prediction In		49	49	49	49	50	51	30
Viewshed Prediction Out		2	2	2	2	1	0	19
Correctly Predicted In		4	4	4	4	4	4	3
Correctly Predicted Out		2	2	2	2	1	0	19
Incorrectly Predicted In		43	43	43	43	44	45	27
Incorrectly Predicted Out		0	0	0	0	0	0	1

Table 4.10 Urban Results without building data

This shows that there is vast difference again in the result based on the source of the data. There is little change in the results throughout the highly accurate data. Figure 4.7 shows the trends.

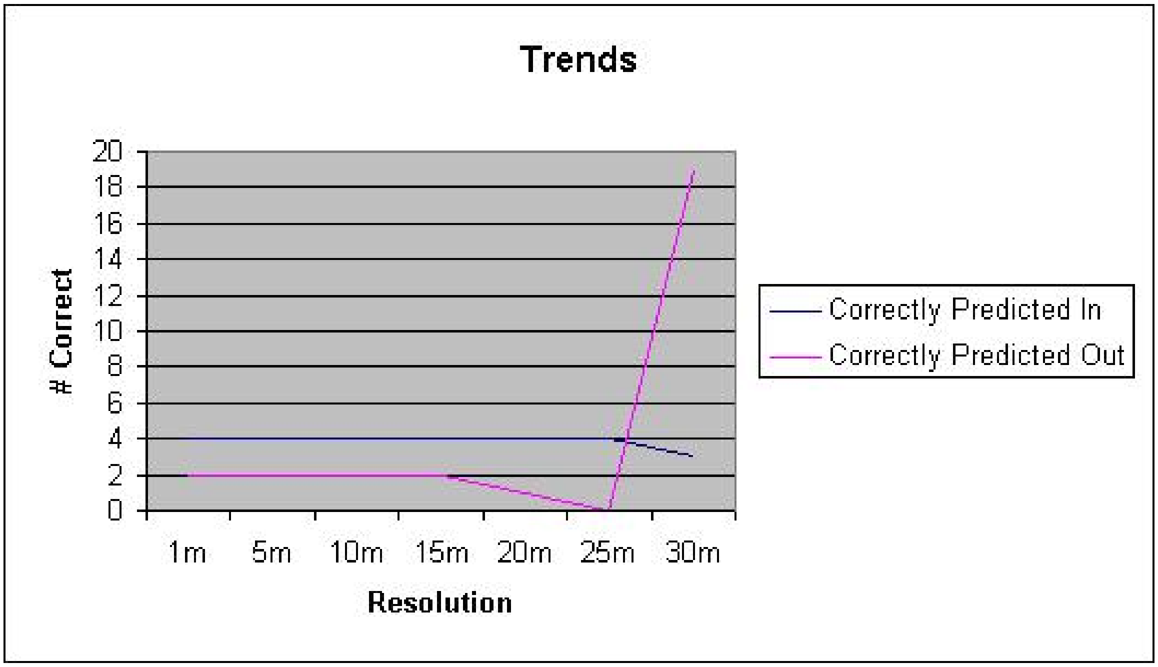
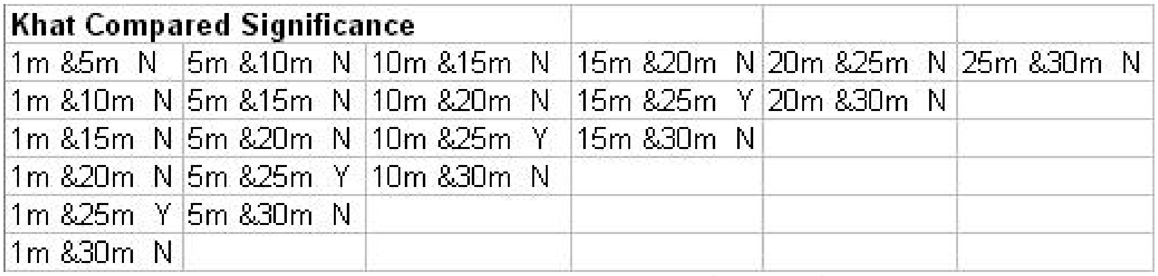


Figure 4.7 Correctly Predicted points for urban area without building data

Here again we see the USGS thirty-meter data doing a much better job overall at predicting the correct values. The same pattern persists; the USGS data does not over-predict the values. The major difference when examining the two types of DEMs seems to be that the USGS has elevation values consistently ten meters from those of the highly accurate data.

Table 4.11 once again proves that the difference between the high-resolution and low-resolution DEMs is minimal. This part of the study again gives merit to companies using the free data for their studies of urban areas.



Khat Compared Significance					
1m &5m N	5m &10m N	10m &15m N	15m &20m N	20m &25m N	25m &30m N
1m &10m N	5m &15m N	10m &20m N	15m &25m Y	20m &30m N	
1m &15m N	5m &20m N	10m &25m Y	15m &30m N		
1m &20m N	5m &25m Y	10m &30m N			
1m &25m Y	5m &30m N				
1m &30m N					

Table 4.11 KHAT Significance test for urban area without building data

4.8. Rural Results Without Buildings

With more and more LMDS systems being deployed in rural areas, this data will be just as useful as the urban results without buildings and most likely be combined with it. If the free USGS thirty-meter data does as well or even close to the accuracy of the more accurate, higher resolution data it will mean much less cost in determining LMDS coverage. The results are shown in Table 4.12.

Rural - Resolution - No Blds	1m	5m	10m	15m	20m	25m	30m
Viewshed Prediction In	29	28	28	29	28	29	24
Viewshed Prediction Out	0	1	1	0	1	0	5
Correctly Predicted In	13	13	13	13	13	13	12
Correctly Predicted Out	0	1	1	0	1	0	4
Incorrectly Predicted In	16	15	15	16	15	16	12
Incorrectly Predicted Out	0	0	0	0	0	0	1

Table 4.12 Rural Results without building data

The results of this portion of the study show that there is little benefit to gather highly accurate data at lower resolutions over the free data. Once again the USGS data does somewhat better as shown by Figure 4.8.

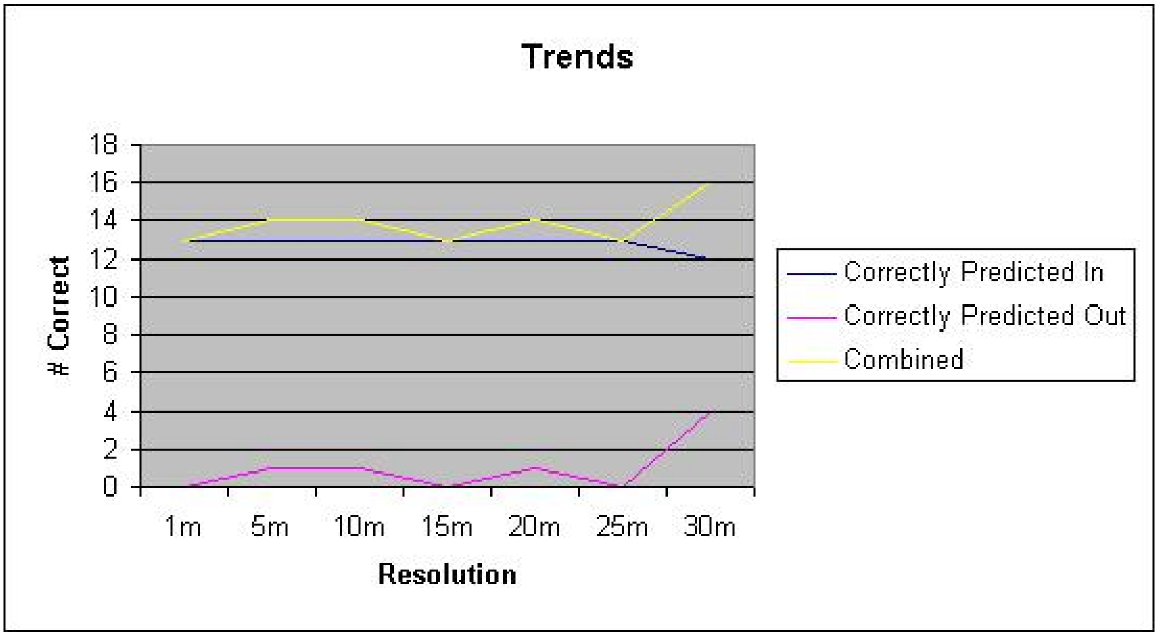
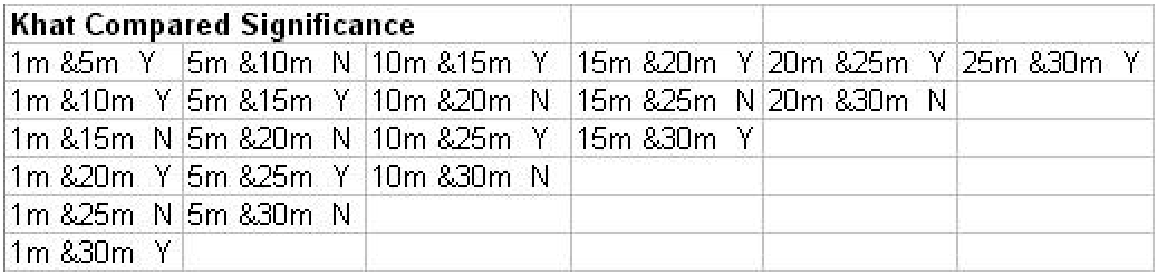


Figure 4.8 Correctly Predicted points for rural area without building data

The proof is shown in Table 4.13 in which once again the free data does significantly better according to the KHAT test.



Khat Compared Significance					
1m &5m Y	5m &10m N	10m &15m Y	15m &20m Y	20m &25m Y	25m &30m Y
1m &10m Y	5m &15m Y	10m &20m N	15m &25m N	20m &30m N	
1m &15m N	5m &20m N	10m &25m Y	15m &30m Y		
1m &20m Y	5m &25m Y	10m &30m N			
1m &25m N	5m &30m N				
1m &30m Y					

Table 4.13 KHAT Significance test for rural area without building data

4.9. Comparison of USGS No Buildings vs. Highly accurate w/ Buildings

Another important issue to look at is the comparison of the highly accurate elevation data with buildings and the USGS data without buildings. The reason for this is that many companies provide building data along with highly accurate elevation data and therefore buildings do not constitute a higher or extra cost. The comparison is shown below with only the thirty-meter data not using building heights.

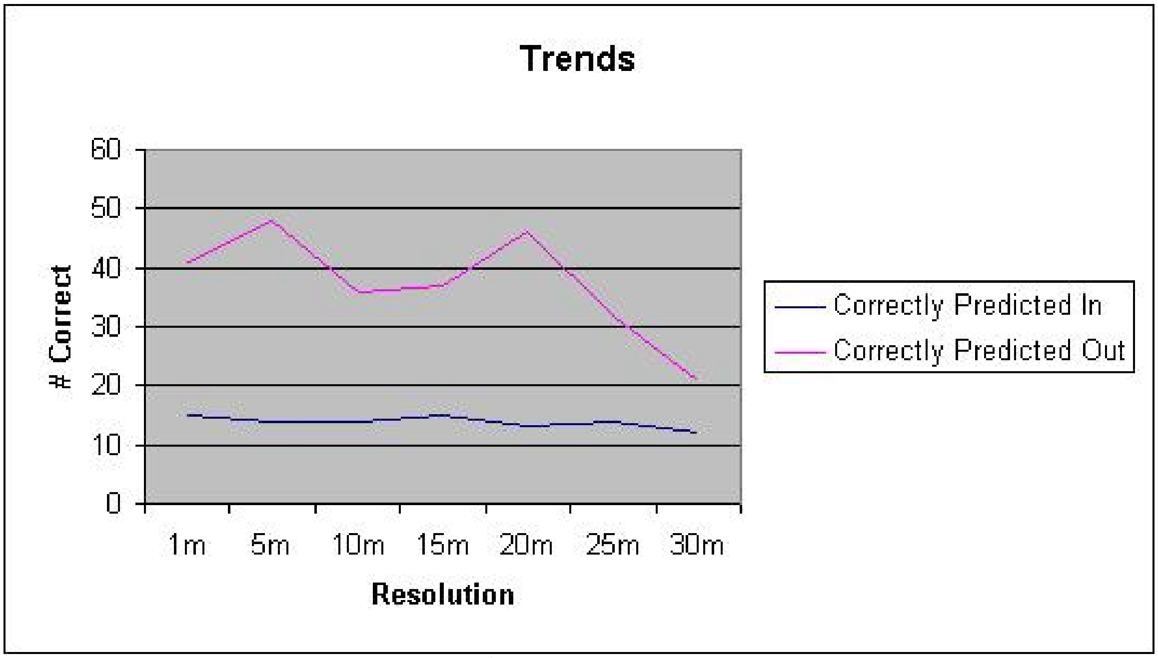


Figure 4.14 Correctly predicted points for highly accurate data with buildings and USGS data with no buildings

This shows that there is a drop in the accuracy as the resolution decreases. More specifically, once the resolution drops below twenty-meters there is a sharp drop in the accuracy of the prediction.

Khat Compared Significance					
1m &5m N	5m &10m Y	10m &15m N	15m &20m N	20m &25m Y	25m &30m Y
1m &10m N	5m &15m Y	10m &20m Y	15m &25m N	20m &30m Y	
1m &15m N	5m &20m N	10m &25m N	15m &30m Y		
1m &20m N	5m &25m Y	10m &30m Y			
1m &25m Y	5m &30m Y				
1m &30m Y					

Table 4.14 KHAT Significance test for highly accurate data with buildings and USGS data with no buildings

The KHAT test shows that there is a difference between the high-resolution with buildings and the thirty-meter free data without buildings. This is both important and unimportant. It is significant because according to this study you will get better results using the high-resolution data with buildings. The insignificance is because only in two of the previous sections were the high-resolution DEMs better than the low-resolution while two were as good and two of the low-resolution DEMs were actually better.

The difference from the one-meter to the thirty-meter data is a combined fifty-six correct versus only thirty-three for the USGS data. The expense of getting highly accurate data (as stated in Chapter 2) is around $350 to $550 per square mile (I-cubed, Inc). This can quickly add up when doing even a small LMDS layout.

Chapter 5: **Conclusions**

5.1 Results

The work described in this study gives insight into the issue of how DEM resolution affects the accuracy of a viewshed using a LOS radio signal. Other topics directly related to this subject were also examined such as whether or not the USGS free DEM would be suitable for a LOS study in different built environments.

Following methods utilized by other researchers, this study found that in some aspects resolution does affect the accuracy of the results. More importantly though, it also found that resolution can have little effect given the terrain type.

The results in chapter 4 demonstrate that only if the high-resolution data with buildings is compared with the free data without buildings does the high-resolution data provide significantly better results. The most important finding is that in every other situation tested the free data results were as good or even better than the high resolution.

Overall, what these results show is that resolution in fact does not have a great effect on the accuracy of a viewshed specifically when it applies to radio wave propagation. In areas where there is significant signal blockage, it may be advantageous to use high-resolution data rather than the freely available low-resolution data because it will give a slightly more accurate result but only if one includes obstruction data such as buildings. Vegetation data would also prove extremely important.

In rural areas it seems that the freely available 30-meter DEM from the USGS may be as good or better than the high-resolution data. This has great implications for LMDS deployments in rural areas.

The significance of the results shown in Chapter 4 are very exciting. LMDS systems are continuously being deployed across the country and with more being deployed in rural areas, these findings will be extremely important. It shows that a study of an area can be conducted with confidence using the freely available data from the USGS. Using the GIS with the USGS data to predict the LMDS system can save potentially thousands of dollars.

The reasons we see that DEM resolution has little effect on wave propagation prediction can most likely be attributed to a lack of vegetation data discussed below.

5.2 Potential Errors

In theory, a LOS algorithm should be able to mimic a LOS signal given “perfect” data. The 1-meter resolution dataset is extremely accurate and yet does not predict the LOS signal very well in the rural area. There could be several reasons for this. Most importantly is the lack of complete data on vegetation. While gathering the field data there was an abundant amount of vegetation (specifically pine) blocking the signal. The effect of this was noted in the field results.

With the freely available data predicting as well as the costly high-resolution data, there is also the potential to add vegetation from the National Land Cover Data from the USGS as well (USGS Geographic Data Download). This inclusion would most likely add to the accuracy of the data.

In the urban area the viewshed algorithm predicted fairly well at each resolution. There were only four points where there was no interference. At the highest resolution, the algorithm predicted two of them unobstructed, while only predicting four points incorrectly as unobstructed. The error that resulted there could be from two sources.

First there could be some error in the algorithm. Two, the rooftops are in reality uneven, but are not represented in the DEM. These two potential errors could be the cause of the inaccurate results of the viewshed.

5.3 Future Work

There are several areas that with more time and money would improve this study. First and foremost, getting accurate and up-to-date vegetation data will be crucial. Secondly, study is needed on different software algorithms to establish which algorithm is best for radio wave propagation prediction. Lastly, getting the building rooftops accurately depicted will also enhance the accuracy of the dataset. Using all of these methods would help improve the results of the study.

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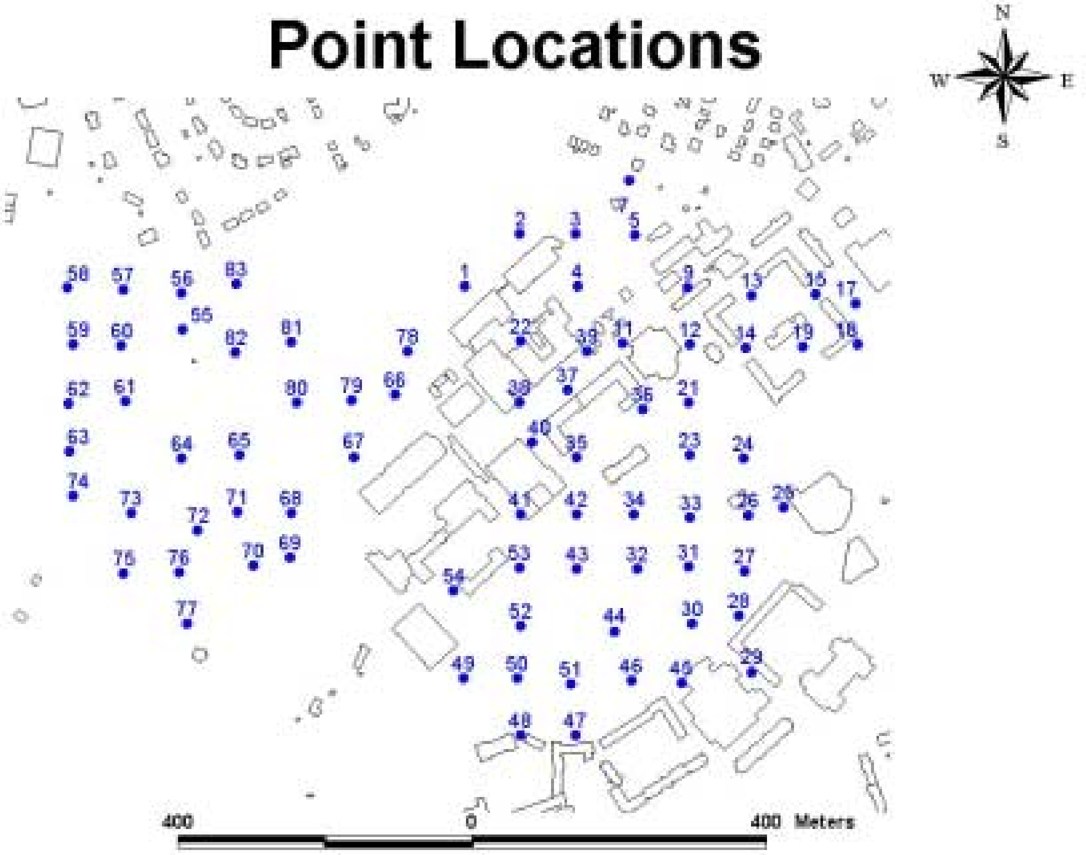
Appendix A

IDA	MEASUREMENT	DISTANCE	BEARING	PATHLOSS	PREDICTED	DIFFERENCE
1	-120	82.08960	0.31608209	98	-56	-64
2	-120	171.09276	26.32662897	105	-63	-57
3	-98	215.79942	44.63158005	107	-65	-33
4	-80	174.03801	62.12031967	105	-63	-17
5	-68	276.69445	56.77960462	109	-67	-1
6	-68	343.07564	62.75884866	111	-69	1
7	-120	318.50171	44.70312766	110	-68	-52
8	-120	411.52358	68.36675277	112	-70	-50
9	-88	314.20545	75.29223167	110	-68	-20
10	-92	244.19958	71.24015539	108	-66	-26
11	-89	215.54527	88.83943501	107	-65	-24
12	-120	305.53444	89.43672246	110	-68	-52
13	-120	396.43274	79.94002346	112	-70	-50
14	-94	382.16877	90.23653973	112	-70	-24
15	-120	481.28117	81.62307983	114	-72	-48
16	-94	473.54164	70.74368439	114	-72	-22
17	-120	534.33278	83.71711963	115	-73	-47
18	-120	534.22429	89.74425355	115	-73	-47
19	-120	459.30668	90.02690700	113	-71	-49
20	-120	464.73739	99.34949447	113	-71	-49
21	-120	313.38756	104.03381865	110	-68	-52
22	-58	76.48608	85.05390399	98	-56	-2
23	-87	340.39325	115.82937853	111	-69	-18
24	-90	409.19995	111.93949557	112	-70	-20
25	-93	485.62054	116.87260782	114	-72	-21
26	-97	448.32641	120.85108019	113	-71	-26
27	-94	488.53162	128.80965611	114	-72	-22
28	-91	523.17343	134.54292442	114	-72	-19
29	-80	590.31781	138.70205500	116	-74	-6
30	-75	487.84155	140.60640145	114	-72	-3
31	-84	427.38827	134.48743572	113	-71	-13
32	-81	383.44914	142.28486552	112	-70	-11
33	-99	385.08822	127.16370566	112	-70	-29
34	-87	325.28378	134.78921619	110	-68	-19
35	-120	215.13931	134.72793671	107	-65	-55
36	-102	257.96699	109.53790574	108	-66	-36
37	-84	151.86036	112.82418398	104	-62	-22
38	-89	107.45108	135.66914889	101	-59	-30
39	-101	166.98687	92.41141009	105	-63	-38
40	-84	160.34758	145.07357762	104	-62	-22
41	-100	241.57804	161.55124296	108	-66	-34
42	-101	274.60063	146.33325710	109	-67	-34
43	-120	339.83393	153.15414133	111	-69	-51
44	-101	438.27926	152.18916606	113	-71	-30

45	-96	545.55734	147.20534750	115	-73	-23
46	-104	508.28028	153.44070874	114	-72	-32
47	-97	550.71110	164.11408986	115	-73	-24
48	-96	534.57220	171.76455878	115	-73	-23
49	-101	452.66296	180.15030787	113	-71	-30
50	-101	458.40890	170.91750305	113	-71	-30
51	-97	481.54873	162.48527812	114	-72	-25
52	-97	388.80689	168.56730328	112	-70	-27
53	-96	311.34540	165.99748780	110	-68	-28
54	-100	332.72762	182.42271691	111	-69	-31

***-120 Measurement was used when no peak was visible**



VITA

Scott Michael Rose

Scott Rose was born April 11, 1977 in Clifton Forge, Virginia. He grew up in White Sulphur Springs, West Virginia until he graduated from Greenbrier East High School. In 1995 he enrolled at Virginia Tech and soon after joined the Geography Department and became interested in Geographical Information Systems. In May of 1999 he completed his undergraduate degree with a GPA of 3.3. During that period he worked as a GIS Technician for the Crop and Soil Environmental Science Department as well as a Cartographer for the Virginia Center for Coal and Energy Research both located at Virginia Tech.

In the fall of 1999, Scott was accepted into the graduate program at Virginia Tech pursuing his Master's in Geography. He accepted an assistantship with the Center for Wireless Telecommunication and worked on several high-speed wireless projects relating to Local Multipoint Distribution Service (LMDS), which eventually became the focus of his thesis. In May of 2001, he received his Master's of Science degree and began work for Lockheed Martin Corporation.