The Validity of Using a Geographic Information System's Viewshed Function as a Predictor for the Reception of Line-of-Sight Radio Waves

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(ABSTRACT)

A Geographic Information System (GIS) viewshed is the result of a function that determines, given a terrain model, which areas on a map can be seen from a given point(s), line or area. In the communications industry, this function has been used to model radio wave coverages and to site transceiver towers for cellular phones. However, there are errors involved with this function and, without the requisite data, it cannot account for building heights that may affect visibility in urban areas. This paper examines the ability to accurately show line-of-sight (LOS) radio wave coverages in order to establish the viability of replacing existing field methods with GIS viewshed analysis.

An origin point capable of supporting a line-of-sight radio wave transmitter was chosen from within the Virginia Tech campus study area. A viewshed analysis was performed with ESRI's ArcView GIS, using this site as the observation point and a 30-meter resolution Digital Elevation Model (DEM) from the US Geological Survey. To check the accuracy of the viewshed, we transmitted at 27.5 GHz, a LOS frequency that has properties common in the wireless telecommunications industry. We also transmitted at 900 MHz from the same point to provide a comparison of the 27.5 GHz frequency to a non-line-of-sight radio wave. Data was then recorded using the following: a digital camera to capture the view from the data point to the transmitter, a Global Positioning System (GPS) receiver to pinpoint the test location, a 27.5 GHz receiver and a 900 MHz receiver to acquire the signals, and a spectrum analyzer to record the strength of both signals. The viewshed model was used as a reference map to define the area of data collection. The recorded data was then entered into the GIS where the visibility attribute of each point (the visual inspection recorded by the camera) was compared to the viewshed's prediction of visibility.

After this comparison, footprints and heights of campus buildings were included in the model, by adding them to the ground heights of the DEM. Another viewshed analysis was performed using the same origin site and the new building height DEM as the elevation grid. This second viewshed was compared with the recorded visibility attribute and signal strength data. The use of more complete surface data was shown to have a more positive correlation with the recorded data than the previous model. The comparison of these two viewsheds demonstrated how well the viewshed function can represent real-world visibility and showed that the accuracy of the viewshed function is dependent on the accuracy of the elevation model.

The signal strength attribute enabled us to create a communications viewshed, or 'commshed'. The commshed consists of all data points that received a signal strong enough to carry data. The building viewshed and commshed were then compared to see to what degree the 27.5 GHz frequency deviates from true line-of-sight paths. There were slightly fewer points in the commshed than points 'in view' in the viewshed model due to the frequency's small wavelength and the lack of vegetation data in the elevation grid. However, when a power margin is added to the transmitter strength in order to overcome unpredictable conditions, the commshed’s predictive accuracy increases as well. This means that for LOS radio systems running under normal operating conditions, the viewshed is an excellent predictor of receiving areas. A 900 MHz commshed was also created so that we could study the relationship between a line-of-sight radio wave and a wave that is not blocked by structures. This comparison showed that, as expected, a viewshed is a better predictor of LOS radio waves than non-LOS waves. The data sets and analysis presented here should help communications companies ascertain the best way to incorporate GIS and the viewshed function into their wave coverage mapping and tower siting processes.

Acknowledgments

I thank Dr. Dennis Sweeney and Willard Farley for helping me to understand the engineering concepts involved with radio wave propagation. I appreciate the help of Ed Manning and Eric Johnson in acquiring the hardware necessary to receive and measure the signals and in understanding the formulae required to estimate the received signal power. I also thank Eric Johnson and Matt Peperak for going out in a cold December to record the signal strengths. Finally, I thank my parents for their patience, love, support, encouragement and friendship.

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Chapter 1. Introduction

Geographic Information Systems

A Geographic Information Systems (GIS) is a computer software system that stores, displays, manipulates, and analyzes information that contains, or can be associated with, a geographic location. The first system was developed in the early 1960's by Roger Tomlinson and was used by the Canadian government to aid in the preservation of natural resources. Since then GIS has evolved into a multimillion dollar industry due to its ability to discover trends and new information about a particular area by placing layers of different types of data overtop of one another and performing varied analyses. It is these varied analyses and their results that allow industry leaders like Redlands, California – based Environmental Systems Research Institute (ESRI) and Troy, New York – based MapInfo to market GIS to numerous, diverse industries. GIS can be used to determine the optimal location for a new retail store, to discover the area impacted by an oil spill at a particular location, or to find trends in criminal activities in a large city. (Greenman, 2000)

GIS Applications in Telecommunications

Over the last ten years, GIS has become an effective tool for businesses because of its unique ability to tie attribute data to specific locations. In the telecommunications industry, "deregulation and increased competition have made GIS a business necessity" (Owen, P. K., 1998, 1). For many telecommunication companies (telcoms), GIS is used only as a facilities management system to handle network maintenance and construction, and to incorporate customer service and billing information into their network geography (Owen, P. K., 1998). However, increased competition has also caused telcoms to seek customers actively, and, as a result of the Telecommunications Act of 1996 and the National Infrastructure initiative, they must also "provide sufficient access to rural communities" (MapInfo, 1997, 11). GIS can help with both challenges by using its data analysis utilities in conjunction with its facilities management features. To find new customers, GIS can locate areas with a high density of persons who meet a particular marketing profile. To serve rural communities, telcoms can use GIS to find the areas with the highest population densities, to map their current facility locations in relation to the potential service area, and to plan the network extension. They can then use the results to estimate the cost of covering new territory. Overall, GIS can benefit telecommunications companies by placing their data in a spatial context and analyzing that data to discover new information on relationships between different data types and by integrating data from different company departments to present a more comprehensive business outlook.

An important part of implementing a wireless network is determining the locations for the base stations. Some of the factors involved in tower siting are the number of customers in a potential area, the terrain of the area, and tower to tower connectivity. GIS can aid in dealing with all of these factors. MapInfo's deciBel Planner, sold as an extension to their GIS software package, is designed for telecommunication companies to use in all aspects of their system rollout. It allows the user to create radio frequency (RF) propagation models, analyze their communication networks, and choose tower sites (MapInfo, 1998). However, this extension is expensive and may include more functionality than some telcoms need or want. Can some functions built into a GIS be used to site towers for certain radio frequencies?

Center for Wireless Telecommunications

In 1996, Virginia Tech's Center for Wireless Telecommunications (CWT), along with the VT Foundation, participated in the Federal Communications Commission's (FCC) auction of Basic Trading Areas (BTA) for Local Multipoint Distribution Systems (LMDS) frequencies. LMDS uses signals centered around 28 GHz of the radio spectrum to transmit data (VIPC, 1996). The signals in this part of the spectrum are millimeter-length waves and are considered Line-of-Sight (LOS) frequencies, meaning that they have characteristics similar to human vision. Once the VT Foundation acquired rights to BTAs in southwest Virginia, CWT needed to develop a method to determine areas that were best suited for implementation of this wireless telecommunications system. With input from the department of Geography, it was decided that the viewshed function of

ESRI’s ArcView GIS should be used as a tool in developing this method. Even though there are documented errors included in this kind of analysis, the time-saving benefits of viewshed analysis, along with the marketing assets of GIS, warrant a study of the viability of using a viewshed as a siting tool for towers broadcasting at LOS frequencies.

Purpose

This study attempts to show that GIS can be used to predict areas that can receive Line-of-Sight radio waves and, thereby, help in locating optimal sites for tower placement. This study will use elevation data that is freely available on the Internet to demonstrate that this analysis can produce acceptable results without large monetary expenditures for base data. First, the accuracy of ESRI’s viewshed analysis function is examined at a large scale to determine how well the viewshed predicts actual visibility. Second, signal strength data is collected at both 27.5 GHz and 902 MHz to be compared with real world visibility and the viewshed visibility prediction. Third, data collected for the two wavelengths are examined to compare the characteristics of a LOS frequency with a non-LOS frequency in relation to the viewshed’s prediction. Finally, the results of this study will be used as base data for future research into creating a GIS commshed function for non-line-of-sight radio frequencies.

Chapter 2. Literature and Research

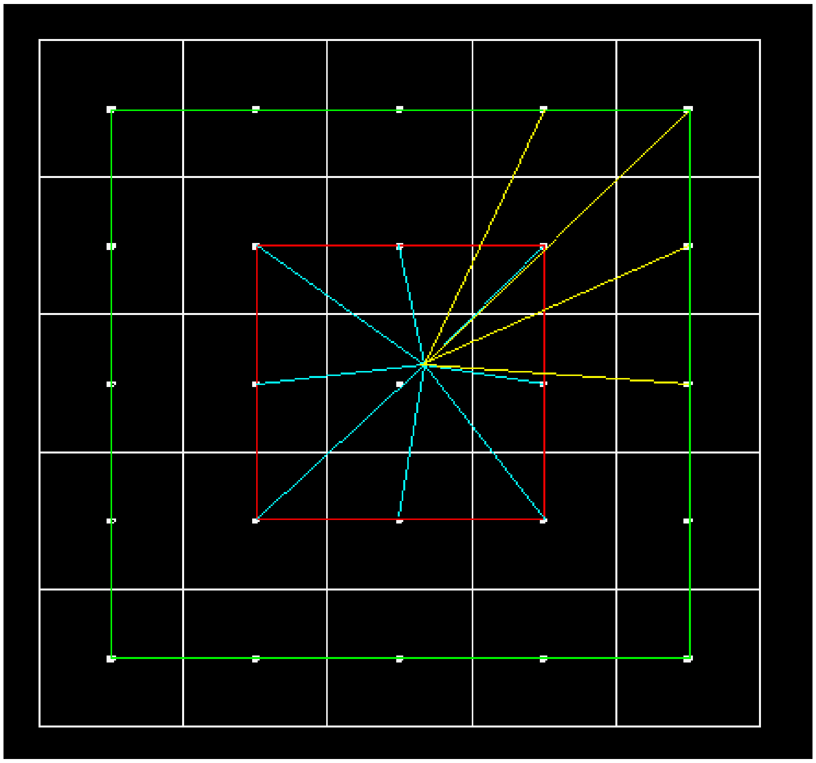
Viewshed Analysis

For wireless telecommunications providers, a GIS viewshed analysis has great potential to help plan network extensions by siting transmitter towers. A viewshed is the result of a function that determines which areas of a map can be seen from a given point, line, or area. Wireless telcoms provide telecommunications access by using portions of the radio spectrum to transmit data. If the wavelength used is a Line-Of-Sight frequency, then a viewshed should show the regions that can receive a signal from a potential tower site. So, given the LOS properties of the wavelength, a viewshed would show the zones able to receive data, called a communications viewshed or 'commshed'. From that information, further viewshed analyses would aid in creating a chain of towers to cover a desired region.

The viewshed algorithm does provide sufficient accuracy for communication coverage at smaller scales, such as a county, when the data being collected are of a general nature, i.e. total population covered or percentage of businesses covered. This is true because the resultant viewshed grid is at a finer resolution than the census data with which it is combined, thus making the census blockgroup the limiting factor for data accuracy, not the viewshed. However, when the scale is increased to the size of a typical communication cell (a 1-3 km radius from a transmitter) and the data gathered become more specific (can this particular home or business receive a signal?), the viewshed grid size becomes the limiting factor because data are needed on specific buildings which are smaller than a grid cell of the viewshed. Therefore, the algorithm and its resulting grid must be examined more closely to determine if the inherent errors are still small enough to allow for accurate prediction of a commshed.

To create a viewshed the algorithm takes a user-defined viewing point (a potential tower site for a commshed) and a Digital Elevation Model (DEM) and computes which cells of the DEM can be seen from the viewing point and which cells cannot be seen. The viewshed is then displayed as a grid of cells coded with 1's for visible cells and 0's for non-visible cells. In order to produce this grid, the algorithm must proceed through several steps. Once the viewing point has been defined, the algorithm determines lines of sight to the cells adjacent to the viewing point, or origin cell. These lines of sight are represented as turquoise lines in Figure 1.1 and the adjacent cells or horizon cells are represented by the red box. Next, the algorithm checks the visibility of the adjacent cells by comparing the elevations of these cells to the elevation of the viewing point cell. If the elevation of a target cell is equal to or greater than the origin cell then it is considered in view and coded with a 1. The elevation angle between the origin and the target cell is then stored. The view horizon is expanded to the next set of neighboring cells (represented by the green box in Figure 2.1).

Figure 2.1 Lines of Sight for Viewshed Computation



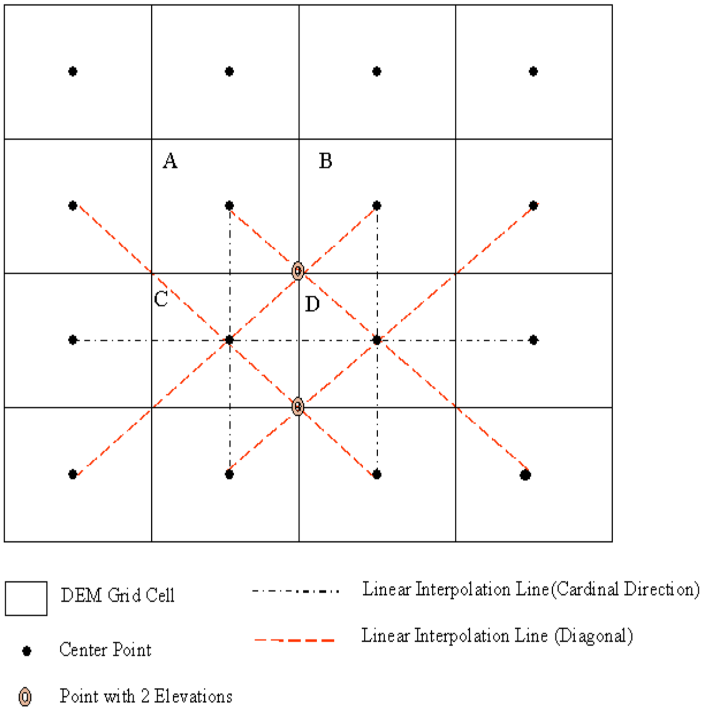
Lines of sight are computed to these cells, shown as yellow lines in Figure 1.1. (Note: not all possible lines of sight are represented in the diagram) To determine visibility for these cells, two angles are computed and compared. First, an elevation is inferred at the point where the line of sight intersects the previous view horizon (where yellow lines intersect red lines in Figure 1.1) and the angle between the origin point and the inferred elevation point is then recorded. The second angle computed is between the origin point and the target point for the green box horizon. If the second angle is larger than the first angle, then the target cell is coded as visible and the larger second angle is stored in place of the previous horizon angle. If the first angle is larger than the second, then the target cell is coded as non-visible. The view horizon is again expanded, elevations are inferred, angles are computed and the largest is stored to compute visibility. This process is repeated until all cells of the grid are coded (Clayton Crawford, ESRI).

Viewshed Accuracy

The accuracy of the resultant grid depends on several variables. The viewshed grid is based on the DEM grid, meaning that the resolution of the DEM determines the resolution of the viewshed and the location of each DEM cell determines the location of each corresponding viewshed cell. Therefore, the first accuracy issue is the accuracy of the DEM. The United States Geological Survey (USGS) is the agency responsible for creating DEMs and reports the horizontal Root Mean Square Error as up to 15 meters and the vertical RMSE as 7 meters. This means that at any given point of the viewshed grid, the location of the cell could be as much as 15 meters away from the actual site of the land it represents. The vertical error affects the viewshed grid by causing some non-visible cells to be coded as visible, and vice-versa, because of an incorrect representation of the ground elevation of up to 7 meters.

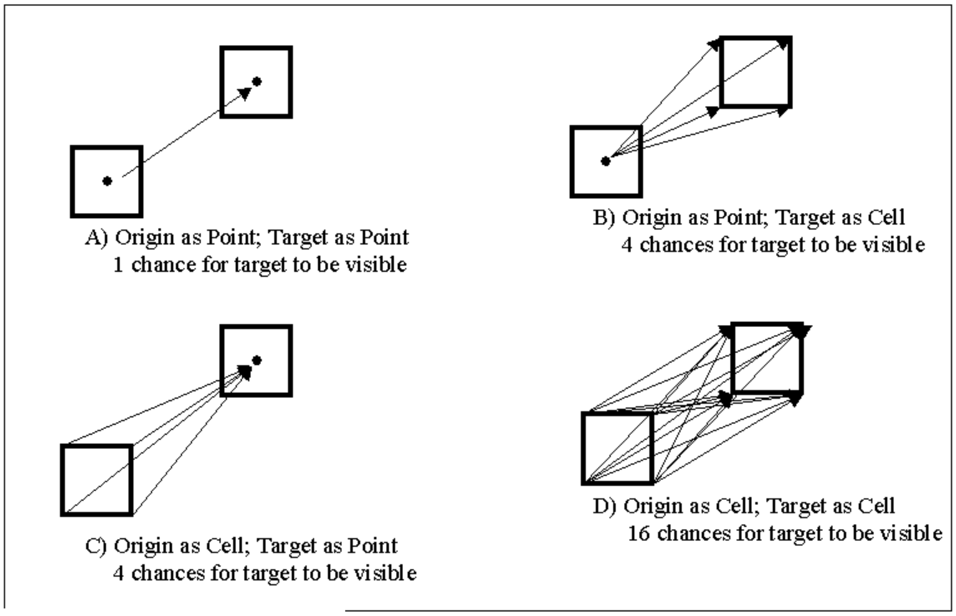
There are two major sources of error within the algorithm itself. The first is how the algorithm infers elevations from the DEM. There are four different ways that a viewshed algorithm can infer elevations. They are “linear interpolation between grid neighbours, triangulation of the grid, grid constraint of the [DEM] mesh, and the stepped model.” (Fisher, 1993, 335) The stepped model can be visualized as a collection of rectangular rods standing on end, with the elevation value the same across the entirety of each cell. No matter where a line of sight crosses a cell, the elevation will be the same, the original value from the DEM. A linear interpolation assigns the elevation value of a cell to the center point of that cell and then interpolates elevations to the center points of the cell's four cardinal neighbors. When a LOS crosses one of these lines, the algorithm uses the interpolated height to compute the viewing angle. The next interpolation method, triangulation of the grid, does the same as a linear interpolation but includes interpolated lines to the diagonal neighbors of the cell. The algorithm addresses the LOS and interpolated line intersection in the same manner as the previous method. However, since the inclusion of the diagonals can cause the same point to have two different interpolated elevations, the algorithm must choose which set of diagonals to use, depending on the location of the origin point. In Figure 2.2 the intersection of lines AD and BC could have two different elevation values based on the interpolation of the DEM from cell center D to A and from cell center C to B. In order to solve this ambiguity, the algorithm uses the interpolation lines that run perpendicular to the diagonals from the origin point to determine visibility. If cell C is the origin point then the network of diagonals containing line AD would be used. If the viewing point is moved to cell D then the diagonal network containing line BC would be used. A grid constraint of the DEM mesh assigns new elevations for eight points for each cell. Each corner of a cell is given the mean of the four cells surrounding a particular corner. Using Figure 2.2 to illustrate this, the intersection of lines AD and BC is also a corner of cell D. This point would be assigned an elevation that is the mean of the elevation values of cells A, B, C, and D. The midpoints between the corners are also given new elevations. Again, using Figure 2.2, the point where line BD crosses into cell D is assigned the mean of cells B and D, while the point where line CD crosses into cell D is assigned the mean of cells C and D. The same process is followed for the midpoints on the south and east sides of the cell. All four of these elevation inference methods result in errors in the viewshed, with the stepped method resulting in the smallest viewshed and the linear interpolation between grid neighbors resulting in the largest.

Figure 2.2 Linear Interpolation for Elevations



The second major source of error in the viewshed algorithm is the treatment of the origin and target positions. Each spot can be treated as a point or a cell, giving four options: origin as point-target as point (Figure 2.3A), origin as point-target as cell (Figure 2.3B), origin as cell-target as point (Figure 2.3C), and origin as cell-target as cell (Figure 2.3D). For points, the algorithm computes only one Line-of-Sight, while for cells it computes four, one for each corner. More computed Lines-of-Sight mean more opportunities for the target to be coded as visible. Again, all four methods result in errors in the viewshed, with the point-to-point option yielding the smallest viewshed and the cell-to-cell option yielding the largest (Fisher, 1993).

Figure 2.3 Treatment of Origins and Targets



A viewshed does have errors; those inherited from the DEM and those inherent in the algorithm. But are these errors enough to prevent the viewshed from serving as a predictive model for LOS radio waves? To answer this question it is necessary to examine these frequencies and how they are used.

Local Multipoint Distribution Service

In the last four years telecommunications companies have been studying LOS frequencies for use in Local Multipoint Distribution Services (LMDS). LMDS uses a broad band of the radio spectrum, from 27.5 to 31 GHZ, to provide communication services. These LOS frequencies can, over short distances (1-3 kilometers), allow wireless transmission of 8,000 high-density photos per second, provide Internet access at 100 times current modem rates, or carry more than 200 video channels simultaneously. (ECE Connection, 1998). It can provide these services at significantly reduced prices compared to current providers because of the large size of the spectrum used. (VIPC, 1997, 4) Because it is a wireless system, LMDS has another advantage over its land-based data delivery system competitors, since it has notably lower costs for building its infrastructure and has a shorter time to market. The infrastructure savings come from the fact that the system needs to be built only to the base stations before seeking customers. Then, once customers are acquired, the receiving end equipment needs to be built and installed only on a per customer basis. Wired systems must deploy their equipment to an entire neighborhood before acquiring customers, costing more and taking more time than an LMDS rollout (Gray, 1996).

There are definite advantages to using LMDS, but there are also limitations to the system. Because the wavelengths are so short (millimeters), heavy rainfall can seriously reduce the signal received. Another limitation is distance. Signals can only be received at appropriate levels over short distances, thus making LMDS a cellular system. Also, data sent at faster rates can not travel as far as data sent more slowly, thereby adding another constraint to the cell size. Finally, the LOS characteristics of the LMDS waves force the transmitters and receivers to be in view of each other, again limiting the size of the cell. This restraint also makes it necessary to thoroughly plan the base station network and shows the need to "develop models that can be used to more accurately predict coverage rates as a function of link margins, antenna heights, obstacles, [and] hub radii" (Gray, 1996).

Chapter 3. Methodology

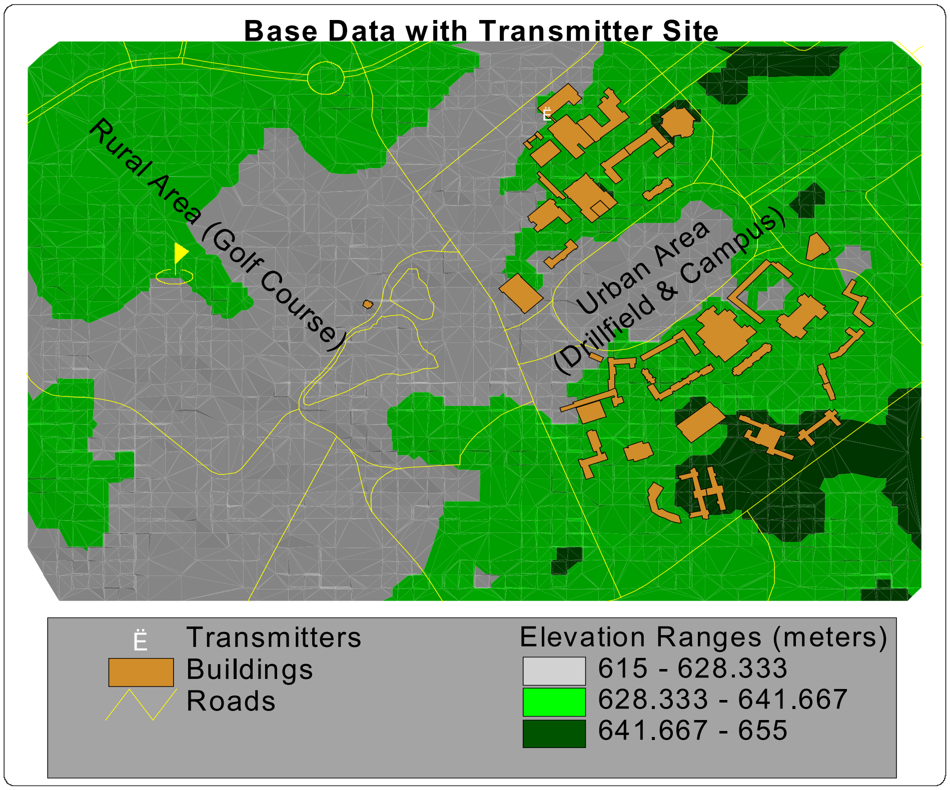
Tower Site and Study Area Selection Process

We chose two sections of the Virginia Tech campus for our study area; the main campus surrounding the Drill Field and the university golf course. The former consisted of tall, closely spaced buildings, representative of an urban environment, while the latter represented a more rural area with rolling hills and trees. This study area was chosen so that we could examine the viewshed algorithm's characteristics and the wavelengths' influences in both settings. The roof of Whittemore Hall was selected as the tower site so that the transmitters could reach the entire study area from one location. (Map 3.1)

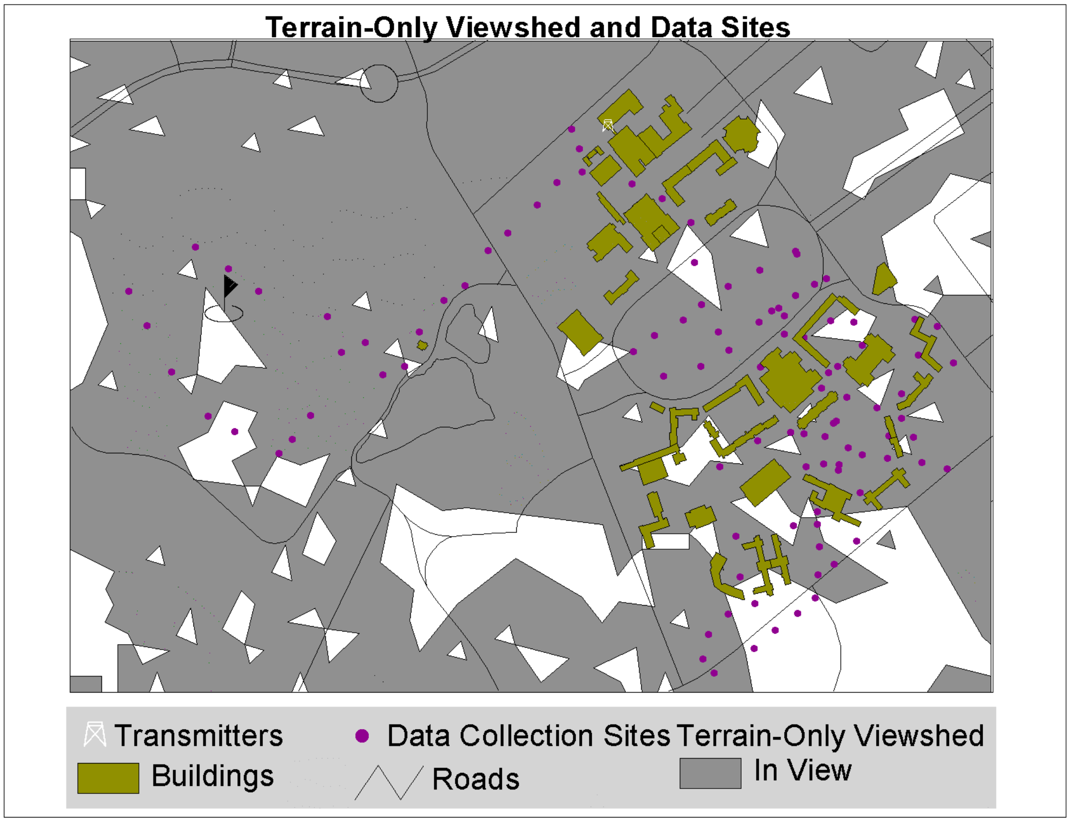
Base Data for the Study Area

Base data consisting of elevations, roads and buildings were then collected. Terrain elevations were acquired from the United States Geological Survey as a 1:24,000 scale DEM of Blacksburg, Virginia. The road and building data came from Virginia Tech's Capital Design and Construction Department as AutoCAD .dwg files, which contained all structures and streets within the Blacksburg town limits. Since the road and building data were in the Virginia South zone of the State Plane Coordinate System, the DEM was converted into the same system and zone so that the data could be viewed together and analyzed. All base data were then imported into the GIS.

Map 3.1 Base Data with Transmitter Site



Map 3.2 Terrain-Only Viewshed and Data Sites



ArcView 3.1 with Spatial Analyst

The GIS used in this study was ESRI's ArcView version 3.1 with Spatial Analyst and 3D Analyst extensions. ArcView's viewshed algorithm treats the targets and origin of the viewshed as points and uses linear interpolation between grid neighbors to infer elevations from the DEM. It also allows limitations to be put upon the viewshed. These limitations are elevation offsets for the origin (transmitter) and targets (receivers), vertical and horizontal constraints of the transmitter beam, and distances from the transmitter to begin and end the viewshed computation.

Compute Terrain-Only Viewshed from Transmitter Site

A viewshed analysis was performed using the transmitter site as the origin, the Blacksburg DEM as the terrain model, and the limitations shown in Table 3.1. The offset-a is the height of the transmitter, offset-b is the height of the receiver, azimuths 1 & 2 define the area from the transmitter that should be used for computation, vert 1 & 2 define the angle of view from the transmitter, radius 1 is the distance from the transmitter where the viewshed computation should start, and Radius 2 is the distance at which the computation should stop. The resultant grid will be referred to as the Terrain-Only Viewshed, or the TO Viewshed, as it used only the ground elevations in its computation. This kind of elevation model is sometimes called the Bare Earth model. The building data were then viewed over the TO viewshed to locate sites within the study area from which to collect data. (Map 3.2)

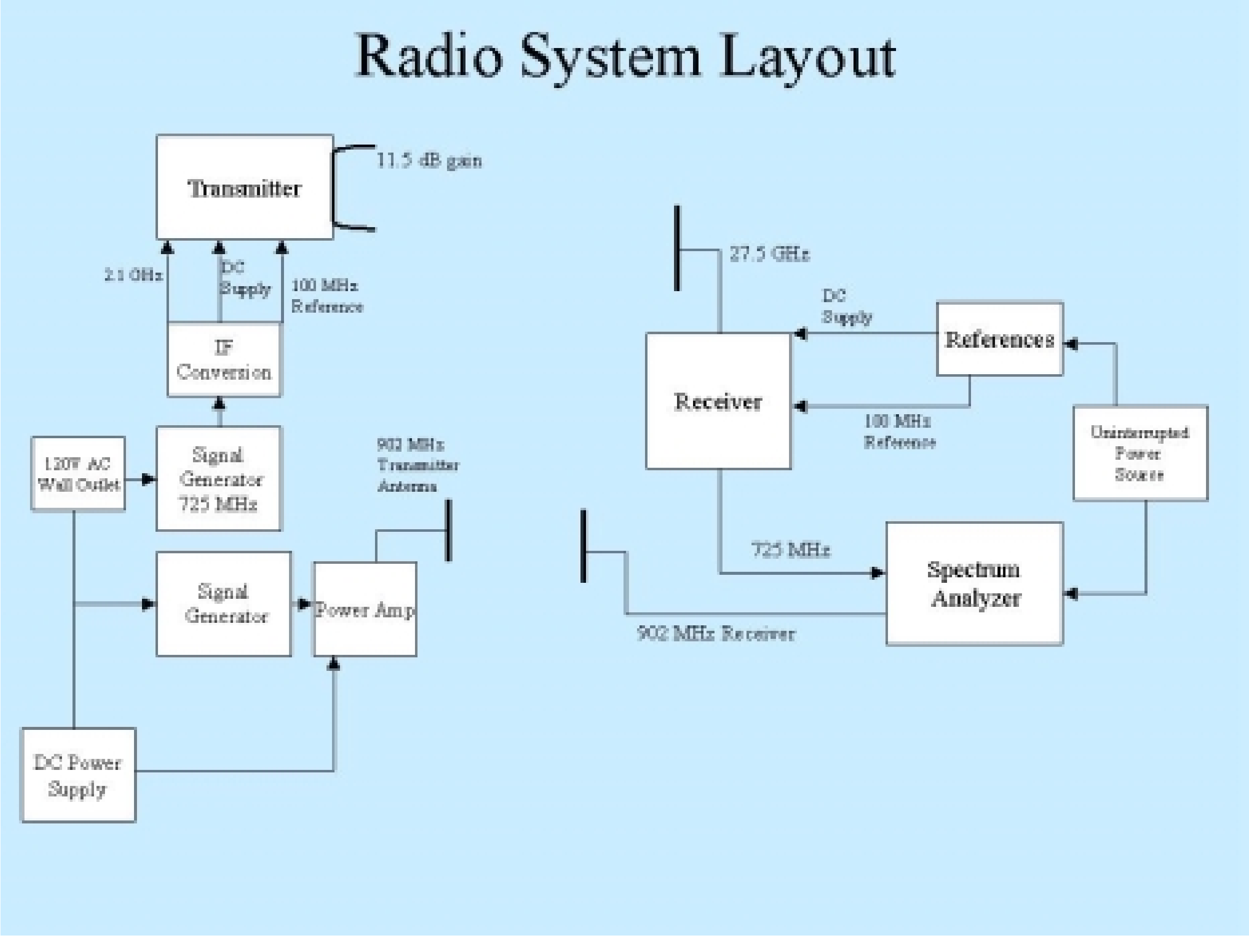
Table 3.1 Constraints for TO Viewshed

ID	OFFSETA	OFFSETB	AZIMUTH1	AZIMUTH2	VERT1	VERT2	RADIUS1	RADIUS2
1	40.00	1.98	0.00	360.00	90.00	-90.00	0.00	5280.00

Receiver Hardware Assembly

To record the necessary data, CWT created a Mobile Receiver Carrier (MRC) to house an antenna and a receiver for 902 MHz and 27.5 GHz. The MRC used a 120 Volt Uninterrupted Power Supply (UPS) to run a 100 MHz reference and DC power supply to a Ka Band Low Noise Receiver that connected to a receiver panel via a 27.5 GHz flexible waveguide. The Ka Band Low Noise Receiver was also connected to a Hewlett-Packard 8594E Spectrum Analyzer (also powered by the UPS) that allowed us to measure the signal strength received from the 27.5 GHz transmitter. The 902 MHz antenna was connected to the Spectrum Analyzer to measure the received signal strength at that frequency. The final component of the MRC was a Corvallis Geographic Positioning System (GPS) unit that allowed us to record the position of each data point and its corresponding signal strengths into a table that could be imported into the GIS. (See Figure3.1)

Figure 3.1 Radio System Layout

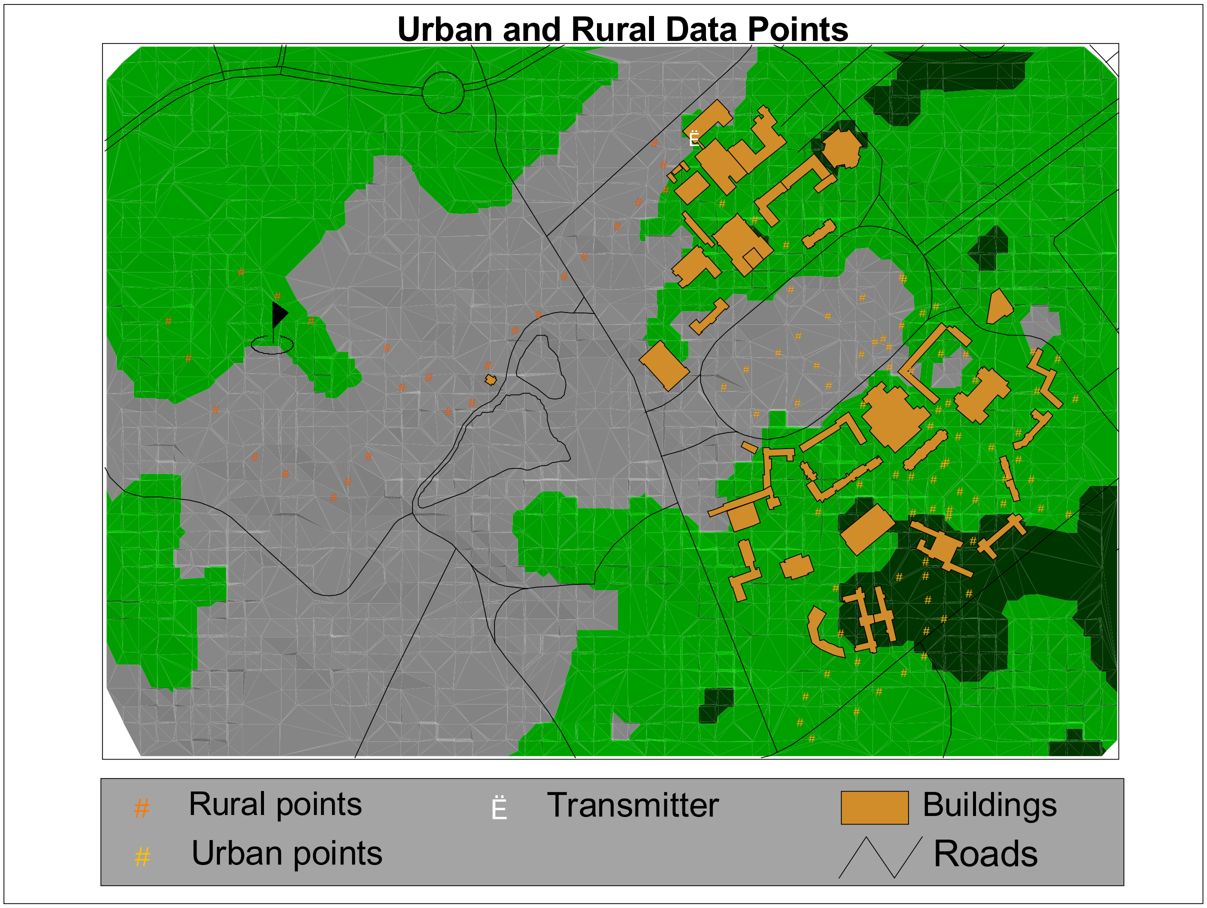


902 MHz + 27.5 GHz Transmitter Hardware Assembly

The transmitters were assembled with the following equipment. To send a radio signal at 27.5 GHz, a Hewlett-Packard 8648C Signal Generator, powered by a 120 Volt AC wall outlet, sent a 725 MHz signal to an Intermediate Frequency Converter and a DC power supply to a 27.5 GHz transmitter. The Intermediate Frequency Converter supplied references at 2.1 GHz and 100 MHz. The transmitter was then fitted with a small horn antenna to allow the signal to travel along a 60-degree beam and cover an entire area, either urban or rural, constantly. A 902 MHz signal was achieved by sending a 75 MHz signal from a Hewlett-Packard 8640B Signal Generator, again powered by a 120 Volt AC wall outlet, to a power amplifier to increase the signal strength emitted. An AC/DC power inverter powered the power amplifier and connected to a 902 MHz transmitter antenna, which broadcast the signal in all directions. (See 3.1) Once assembled, the transmitters were positioned on the southern corner of the Whittemore Hall rooftop and the 27.5 GHz transmitter was centered at 140 degrees from North to allow full coverage of the urban environment.

The Ka Band Low Noise Receiver, the Intermediate Frequency Converter and References, and the 27.5 GHz transmitter were loaned to CWT by mm-Tech, Inc., an Eatontown, New Jersey-based broadband wireless communications company, for use in studies of LMDS frequencies.

Map 3.3 Urban and Rural Data Points



Data Collection

After erecting the transmitters, we navigated the MRC within the campus area and recorded data at 77 different sites. The 27.5 GHz transmitter was then re-centered to 240 degrees so we could record data at 26 sites within the golf course area. (See Map 3.3) For each site the following procedure was followed:

1) We recorded the position of the MRC and whether the transmitters were visible from that location.
2) If the transmitters were not visible, the obstruction blocking the line of sight was recorded.

3) We then rotated the 27.5 GHz receiver panel to locate the strongest signal level as displayed on the spectrum analyzer and documented it.
4) The 902 MHz antenna was then connected to the spectrum analyzer and its signal strength was recorded.
5) All data were stored in a table in the GPS.

The signal strengths were recorded in decibels above 1 milliWatt (dBm) and the noise floor for the study was minus -105 dBm. After collection of the data, the GPS positions were adjusted using differential correction and the data table was converted into an ArcView-compatible format using PC_GPS software. The table was then imported into the GIS (Table 3.2) and the points projected into the Virginia South zone of the SPC system.

Table 3.2 Recorded Data for All Points

NUMBER	IN VIEW?	OBSTRUCTION	SIGNALSTRENGTH	902MHZ_STR
1	YES	NONE	-26.66	-50.8
2	NO	BUILDING	-48.5	-65
3	YES	VEGETATION	-32.5	-60.7
4	NO	BUILDING	-71.5	-76.8
5	NO	BUILDING	-77.2	-82.5
6	NO	BOTH	-80	-74.5
7	YES	NONE	-38.6	-68.7
8	NO	BUILDING	-66.2	-85.6
9	NO	BUILDING	-75.9	-79.1
10	NO	BUILDING	-59.9	-74.8
11	NO	BUILDING	-61.88	-73.15
12	NO	BUILDING	-56.98	-63.58
13	YES	VEGETATION	-54.48	-66.75
14	NO	BUILDING	-66.91	-82.18
15	NO	BOTH	-74.17	-82.72
16	NO	BOTH	-70	-86.75
17	NO	BOTH	-86.94	-93.08
18	NO	BOTH	-65.68	-79.44

19	NO	BOTH	-72.62	-88.9
20	NO	BOTH	-60.45	-85.83
21	YES	VEGETATION	-44.85	-69.03
22	YES	NONE	-32.74	-67.1
23	NO	BOTH	-59	-72.41
24	NO	BOTH	-69.58	-72.69
25	NO	BOTH	-63	-75.35
25	NO	BUILDING	-50.8	-68.28
26	NO	BUILDING	-82.39	-98
27	NO	BUILDING	-78.23	-88.92
28	NO	BOTH	-87.14	-95.5
29	NO	VEGETATION	-46.9	-78.87
30	NO	BUILDING	-57.4	-86.6
31	YES	NONE	-32.62	-71.9
32	YES	NONE	-40.43	-77.31
33	NO	BUILDING	-62.23	-8102
33	NO	BOTH	-83.64	-93.27
34	NO	BUILDING	-76.36	-102.51
35	NO	UNKNOWN	-67.02	-86.91
36	NO	BUILDING	-101.86	-95.99
37	NO	BUILDING	-999	-85.78
38	NO	BOTH	-40.17	-72.78
39	NO	BUILDING	-66.25	-92.51
40	NO	BUILDING	-67	-81.42
41	NO	BUILDING	-83	-89.11
42	NO	BOTH	-73.88	-84.05
42	NO	BUILDING	-55.42	-75.33
43	NO	BUILDING	-999	-999
44	NO	BUILDING	-81.18	-89.13
45	NO	BUILDING	-80.62	-83.55
46	NO	BUILDING	-83.11	-98.7
47	NO	VEGETATION	-75.08	-86.11
48	NO	VEGETATION	-999	-94.1
49	NO	BOTH	-89.54	-86.92
50	NO	BOTH	-90.13	-100.98

51	NO	BUILDING	-90.39	-90.13
53	NO	BUILDING	-76.36	-85.26
54	NO	BUILDING	-64.15	-77.89
55	YES	NONE	-45.81	-73.96
56	NO	BUILDING	-82.51	-88.85
58	NO	BUILDING	-71.77	-98.73
59	NO	BUILDING	-89.23	-98.18
60	NO	BUILDING	-77.61	-98.67
61	NO	BOTH	-84.41	-84.42
62	YES	VEGETATION	-56.47	-74.95
63	NO	BUILDING	-79.56	-82.69
64	NO	BUILDING	-73.05	-83.22
65	NO	BOTH	-79.65	-81.8
66	NO	BOTH	-68.57	-83.26
67	NO	BUILDING	-79.77	-87.51
68	NO	BUILDING	-69.72	-78.12
69	NO	BUILDING	-74.94	-92.6
70	NO	BOTH	-92.93	-92.05
71	NO	BUILDING	-82.66	-93.53
72	NO	VEGETATION	-74.29	-84.28
73	NO	BUILDING	-79.05	-83.16
74	NO	BUILDING	-79.91	-88.31
75	NO	BUILDING	-73.79	-92.87
76	NO	BUILDING	-76.52	-80.57
77	NO	BUILDING	-64.3	-77.42
78	NO	BUILDING	-77.7	-83.43
79	NO	BOTH	-79.47	-91.84
80	YES	VEGETATION	-52.48	-77.58
83	YES	NONE	-53.13	-80.45
84	YES	NONE	-21.34	-50.26
85	YES	NONE	-38.73	-55.79
86	YES	VEGETATION	-57.01	-62.82
87	YES	NONE	-25.16	-59.5
88	YES	NONE	-30.56	-65.65
89	YES	NONE	-40.7	-57.91

90	YES	NONE	-53.55	-66.3
91	NO	VEGETATION	-56.8	-64.1
92	YES	VEGETATION	-54.17	-66.52
93	YES	NONE	-40.41	-74.46
93	YES	NONE	-33.74	-74.55
94	YES	NONE	-37.14	-67.09
95	YES	NONE	-39.66	-71.02
96	YES	NONE	-55.79	-78.51
97	NO	HILL	-61.26	-86.56
98	NO	HILL/VEG	-71.54	-95.84
99	YES	NONE	-44	-80.1
100	NO	VEGETATION	-54.96	-73.16
101	YES	NONE	-46.26	-72.58
102	NO	VEGETATION	-71.68	-84.75
103	NO	VEGETATION	-65.5	-84.75
104	YES	NONE	-43.72	-70.85
105	NO	VEGETATION	-61.98	-77.9
106	YES	NONE	-40.63	-65.63
107	YES	NONE	-35.93	-67.07
108	NO	VEGETATION	-44.14	-68.93
109	NO	BUILDING	-72.41	-78.25

Next, building height data were recorded. To accomplish this, we used a surveyor’s sight and a tape measure to perform triangulation on each building within the study area that obstructed the view from any data point. The highest point of the building was used in determining its height in order to produce a restrictive terrain model for a second viewshed analysis. The building heights were added as a new column in the building layer of the GIS. (See Table 3.3)

Table 3.3 Building Heights

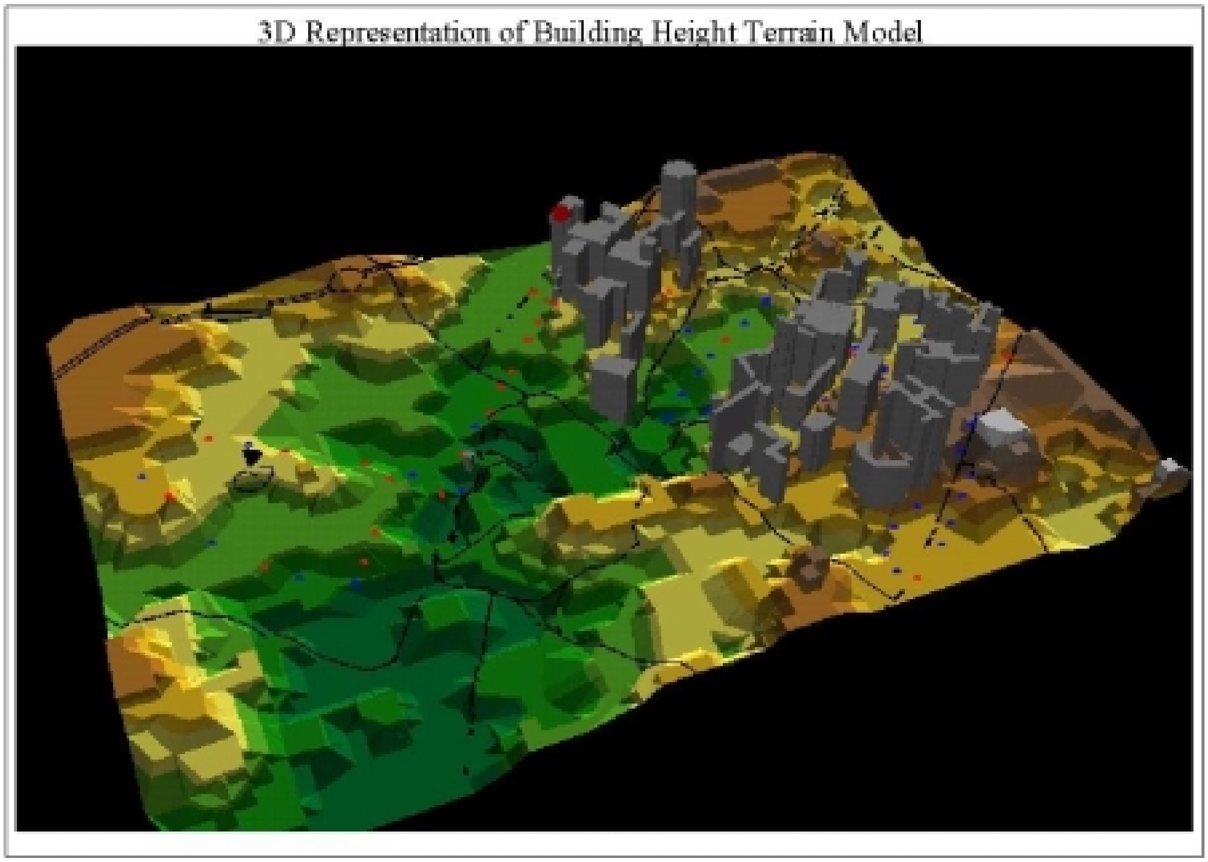
NAME	ELEVATION(m)	NAME	ELEVATION(m)
Agnew Hall	4.1	Norris Hall	13.56
Ambler JohnstonE	21.27	O'Shaughnessy N	23.92

Ambler JohnstonW	21.27	O'Shaughnessy S	23.92
Burke-Johnson Ce	9.75	Owens Hall	15.09
Burruss Hall Low	13.4	Pamplin Hall	17.18
Burruss High	20.7	Patton Hall	16.36
Campbell Hall	14.56	Payne Hall	11.92
Cheatam Hall	15.47	Pritchard Hall	15.7
Clubhouse	4.3	Randolph Hall	11.9
Cochran	15.89	Sandy Hall	11.61
Cowgill Hall	18.91	Seitz Hall	19.91
Dietrick Hall	11.57	Slusher Tower	33.59
Eggleston	14.86	Slusher Wing	11.27
Engel Hall	13.72	Smyth	20.41
Hancock Hall	13.4	Temp Bldg 1	4.09
Holden Hall High	13.79	Temp Bldg 2	4.09
Holden Hall Low	5.59	Temp Bldg 3	4.09
Lee Hall	25.82	Vawter	12.42
McBryde	23.9	War Memorial	18.78
Newman	14.85	Whittemore Hall	37.39
		Williams Hall	15.83

Buildings-Added Viewshed

In order to create a viewshed that includes building heights in its analysis, the building elevations must be added to the ground elevations at the correct locations. The first step in this process was to convert the buildings layer to a grid with the elevations as the cell values; all non-building cells were assigned a value of zero. Next the building grid and the DEM were resampled from 30-meter resolution to 5-meter resolution to allow for a more accurate overlay of the building heights onto the terrain elevations. This resampling caused a significant increase in the number of cells to be processed, so, to reduce processing time, both grids were clipped to the study area. The roads layer was also clipped for display purposes. The fourth step was to create a new elevation grid by adding the building grid to the terrain grid. A viewshed analysis was then performed using the Buildings-Added DEM and the transmitter site as the origin. The limitations of the new BA Viewshed were the same as the limitations for the TO Viewshed with one exception. The elevation offset for the transmitter site was changed from 40 meters to 2 meters to account for the inclusion of the height of Whittemore Hall in the new terrain model. Map 3.4 shows the effects of the buildings on the elevation model along with receiver locations marked as visible (red) or unable to receive data (blue).

Map 3.4 3D Representation of Terrain and Buildings



Commshed Creation

After the viewsheds were created, we needed to create a Commshed for our test frequencies. The first step in this process was to find which points received a signal strong enough to receive data. To decide what would constitute enough strength, we computed the Estimated Received Power (ERP) that would have been measured in a free-space environment using Equation 3.1. A free-space environment is a theoretical model used to represent the atmosphere in outer space where there would be no hindrances to the travel of a radio wave. The variables in the equation are the transmitter power, the gain of the transmitter and the receiver, the wavelength, and the distance from the transmitter to the point. The distance from the transmitter to each data point was computed in the GIS and stored in a new column in the data table. The other variables for 27.5 GHz are in Table 3.4 and in Table 3.5 for 902 MHz. Once the ERP was calculated for each data point, the signal strength recorded, or Actual Received Power (ARP) was subtracted from the ERP to get a difference value.

Equation 3.1 Power **Calculation Equation**

Estimated Power = (Tx Power + Tx Gain + Rx Gain – 21.98 – 20log10 (distance/wavelength)

Table 3.4 27.5 GHz Variables

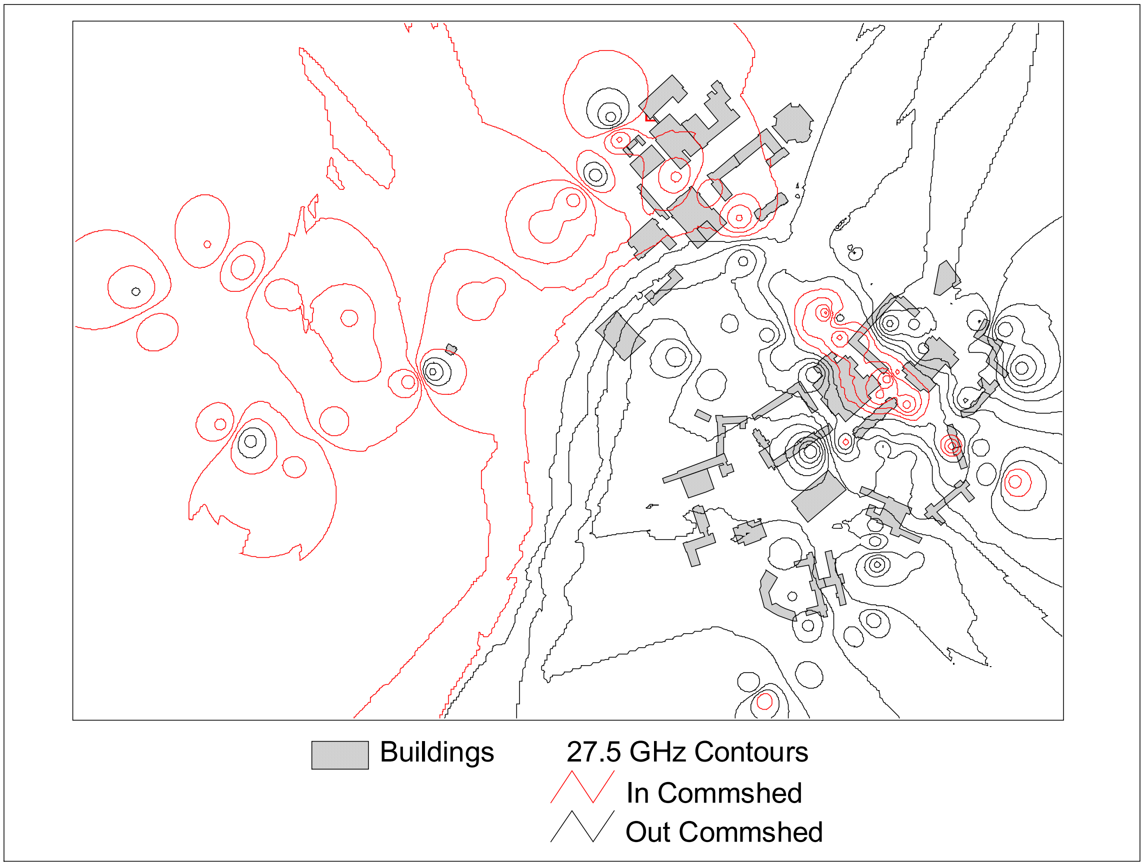
Frequency	2.75E+10	Hz	27.525	GHz
Wavelength	0.010899	Meters	10.89918256	mm
TX Gain (dB)	11.5	dBi	14.12537545	mW
RX Gain (dB)	37	dBi	5011.872336	mW
TX Power (dBm)	22.3	dBm	169.8243652	mW

Table 3.5 902 MHz Variables

Frequency	9.02E+8	Hz	0.902	GHz
Wavelength	0.332594	Meters	332.594235	mm
TX Gain (dB)	5.14	dBi	3.265878322	mW
RX Gain (dB)	5.14	dBi	3.265878322	mW
TX Power (dBm)	21.5	dBm	141.2537545	mW

The difference value was then compared to a threshold value to compute whether a point was in the Commshed or out of the Commshed. The threshold is a variable, recorded in dB, which allows this process to account for discrepancies between the real world and the free space environment, such as rain and vegetation. If the transmitter power is increased by the threshold value, the extra power can be used to overcome real-world obstacles and the signal can still reach the target area with enough power to be received. Different types of topography may need different power margins (thresholds) to account for their real-world obstacles. For this study, threshold values of 10, 20, 30, and 40 dB were used. Because the ARP were recorded as positive dB values, points that had difference values lower than the threshold value were recorded as being in the Commshed. The second step was to create contours from the difference values of each point and display them as below or above the threshold (In or Out of the Commshed), thus showing the areas that can and cannot receive a usable signal. (Map 3.5) Finally, the Commshed status (In or Out) of each point was compared to its status in each of the viewsheds to ascertain the ability of each viewshed to predict each Commshed.

Map 3.5 27.5 GHz Commshed with 10 dB Threshold



Chapter 4. Results and Analysis

Once the data were collected, we used the GIS to determine additional data to aid in our analyses. We then compiled and analyzed them to determine the validity of our hypothesis. We used three processes to analyze our data; error matrices, discrete multivariate analysis, and a power-difference/threshold equation.

We used ArcView's Point in Polygon algorithm to assign values to each data point as in or out of our two viewsheds (TO and BA). We then compared these values with real world visibility values for each point (whether the transmitter could be seen by the data collector). For points that had a disagreement between the actual view and the BA viewshed, we computed the distance between the point and the edge of the viewshed. (Table 4.1) This table shows the following: the *InAct.Vw* column displays whether the transmitter could be seen from the receiver location, the *InBldg.Vw* column shows a receiver location as being within the BA viewshed (a value of 1) or outside the BA viewshed (a value of 0), the *Dist. To InVw* column holds the distance from the receiver point to the closest grid cell coded as in the BA viewshed, and the *Dist. To OutVw* records the distance value to the closest cell coded as out of the BA viewshed. These distances helped us analyze the accuracy of the viewshed borders, which were influenced by the DEM resolution. All of the disagreement datapoints, save one (Numb# 63), are within one grid cell of being in agreement with the BA Viewshed. The coding of receiver point # 63 as out of the BA viewshed appears to be a result of the vertical inaccuracy of the digital elevation model. When standing at receiver location # 63, the transmitter can be seen just above a hill that lies between the transmitter and the receiver location, the top floor of Whittemore Hall cannot be seen from receiver point # 63. The height of the transmitter above the top floor of the building is only six feet, well within the vertical accuracy parameters of the elevation model. The low values of the horizontal distances recorded in Table 4.1 suggest that, if it were necessary, the use of a higher resolution DEM in the viewshed analysis would return fewer points with disagreement between the actual view and the predicted view because the resulting viewshed would have a more finely defined boundary than the DEM used in our study (effects of DEM resolution can be found in Rose, 2001).

Table 4.1 Distance to Opposite Visibility Area

Numb#	In Act.Vw	In Bldg.Vw	Dist. To InVw	Dist. To OutVw
18	NO	1	0.0000	33.6800
26	NO	1	0.0000	23.8154
25	NO	1	0.0000	16.8400
2	NO	1	0.0000	16.8400
22	YES	0	16.8400	0.0000
3	YES	0	16.8400	0.0000
93	YES	0	16.8400	0.0000
99	YES	0	16.8400	0.0000
32	YES	0	37.6554	0.0000
33	YES	0	47.6307	0.0000
63	YES	0	384.0111	0.0000

Error Matrices

Once each data point was assigned three visibility values (TO, BA, Actual), we created an error matrix to assess the site-specific accuracy of each viewshed. The matrices (Tables 4.2 and 4.3) are tables of numbers that represent, for our study, the number of data points that were coded as visible and not visible in relation to the actual visibility of the point. These tables display errors of commission and omission and allow us to compute the percentage accuracy for the viewsheds (Congalton, R. G., et al, 1981, 4).

Table 4.2 TO Viewshed Error Matrix

	TO Viewshed		
ActVw	In	Out	TOVw
In	29	0	29
Out	61	13	74
	90	13	42

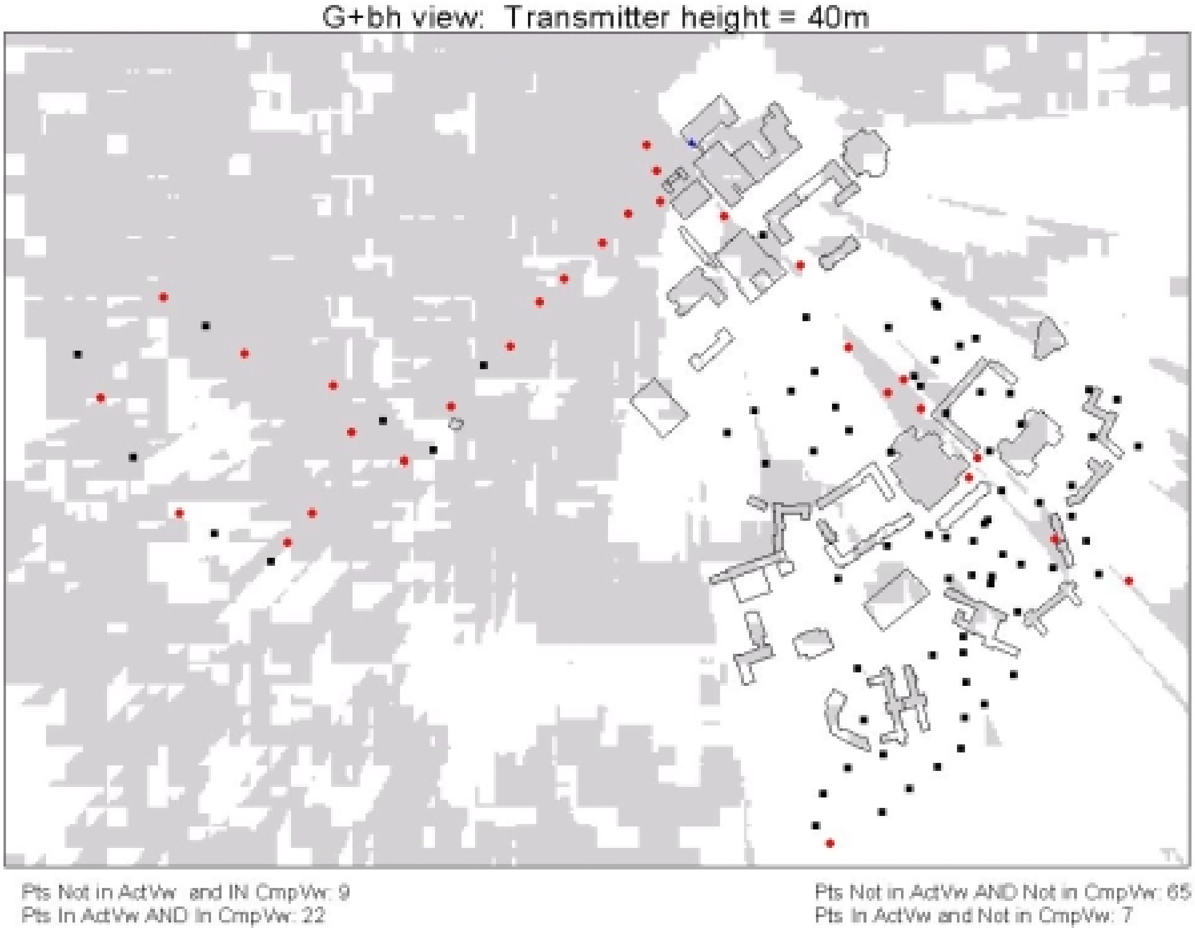
Table 4.3 BA Viewshed Error Matrix

	BA Viewshed		
ActVw	In	Out	BAVw
In	22	7	29
Out	9	65	74
	31	72	87

The Terrain Only Viewshed described in Table 4.2 and shown in Map 4.1 incorrectly predicted the visibility of 61 of our 103 locations. All 61 were commission errors - the viewshed algorithm included them in the viewable area when they were not actually visible. These errors were expected. Since the algorithm did not include building heights in its calculation, we anticipated that it would include areas blocked by buildings as visible. There were no errors of omission - none of the sites that were actually in view of the transmitter were coded as out of view. Forty-two of our sites were correctly predicted (29 in view and 13 out). The percentage accuracy for the Terrain Only Viewshed is 40.77% ((number correctly predicted/total sites) * 100). The Buildings Added Viewshed described in Table 4.3 and shown in Map 4.2 incorrectly predicted the visibility of 16 locations, 9 errors of commission and 7 omission errors. These errors result from the resolution of the elevation model, vertical errors of the elevation model and the building heights, and visibility obstruction due to vegetation. Eighty-seven locations were correctly predicted, 22 in view and 65 out of view. The percentage accuracy for the Buildings Added Viewshed is 84.46%. The error matrices of the two viewsheds suggest that, given the terrain in our study area, adding building heights to an elevation model can more than double the predictive accuracy of a viewshed.

Map 4.1 Visibility of Points over TO Viewshed

Map 4.2 Visibility of Points over BA Viewshed



Discrete Multivariate Analysis

To further assess the accuracy of the viewshed function, we performed a discrete multivariate analysis (DMA) on each viewshed error matrix. This analysis computes the difference between each viewshed prediction and chance prediction of visibility, as well as measuring the similarity of the two viewsheds. DMA produces a value, called KHAT, which indicates the difference between observed agreement of the viewshed and true visibility and chance agreement. The analysis also produces a variance value for a given confidence level for each error matrix. This confidence interval is used to compare the error matrices of the two viewsheds and determine if they are significantly different (Congalton, R. G., et al., 1981).

The KHAT value and the boundaries for that value, given a 95% confidence level, are listed in Table 4.4.

The KHAT values for the two viewsheds show that the BA Viewshed is a much better predictor of visibility as compared to chance prediction than the TO Viewshed is. This is not surprising given the percentage accuracy values of the two viewsheds. Since the two confidence ranges do not overlap, the viewsheds are considered significantly different. Again, this is not a surprise when the change created in the elevation model caused by the addition of the building heights is examined. See Appendix A for the figures used to compute the KHAT and variance values.

Table 4.4 Error Matrices Statistics

Error Matrix	Lower Limit	KHAT	Upper Limit
BA Vwshd	0.61666767	0.62391602	0.63116437
TO Vwshd	0.08138739	0.10714793	0.13290848

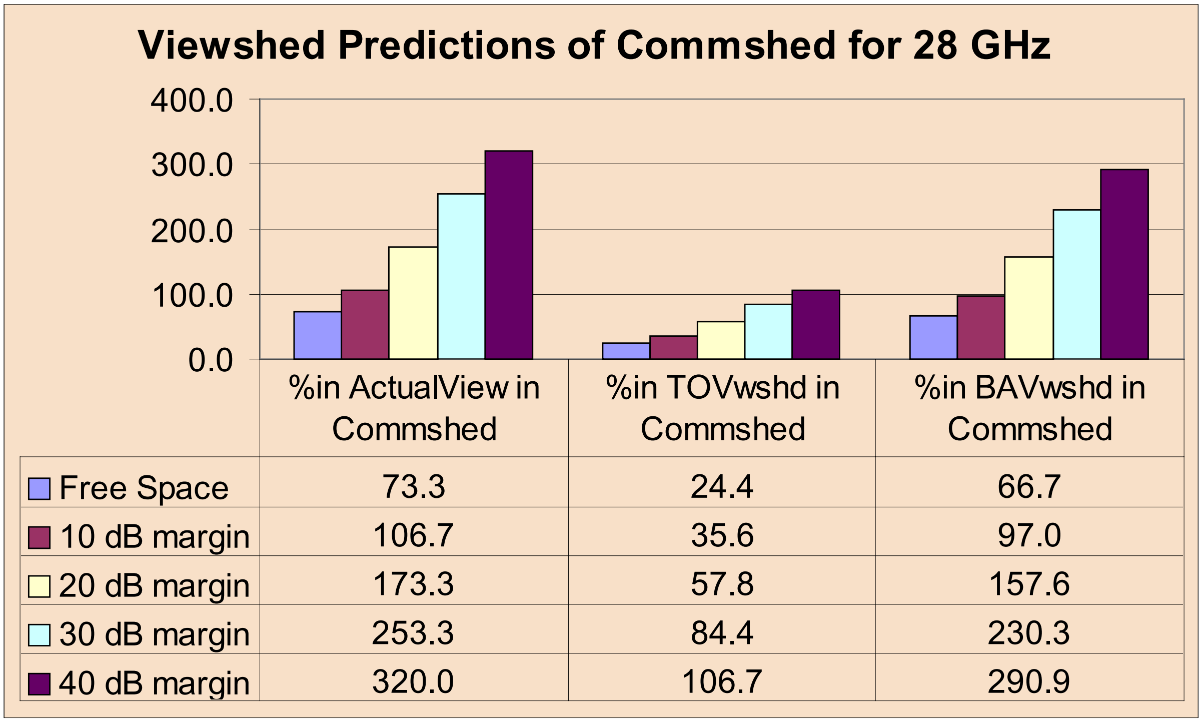
Viewshed Accuracy with Power Margin Commsheds

After the visibility accuracy for the viewsheds was examined, we wanted to determine their communications accuracy for Line-Of-Sight radio waves to see how well the algorithm can predict areas for telecommunications cells. To do this we measured and computed commsheds for 28 GHz, an LMDS frequency, and for 902 MHz, a typical cell phone frequency. We expected the LMDS commshed to have fewer points than the viewsheds because of its short wavelength and the lack of vegetation data in the elevation model, and the 902 MHz commshed to have more points because of the longer wavelength's ability to bend around obstructions. Also, since our study area is not a free space environment, the viewsheds were not expected to mirror the commsheds. As can be seen in Figures 4.1 and 4.2, in a free space environment the viewsheds and the commsheds do not match. However, when the transmitter power is increased, the predictive communications accuracy increases as well.

In most wireless telecommunication applications, the transmitter power is increased by a power margin (a certain number of dB) to compensate for unpredictable real-world conditions such as rain and vegetation. An increase by a power margin of 40 dB is fairly common in these applications, so we chose to examine the effects of power margins of 10, 20, 30 and 40 dB on the commshed predictive accuracy of our viewsheds. The increase in power goes into the power threshold equation and the Estimated Received Power is recalculated and compared again to the Actual Received Power. This process resulted in a new commshed. We then computed the percentage of points that were in a viewshed that also fell into the new commshed. Figure 4.1 shows the results of these analyses for 28 GHz and Figure 4.2 shows them for 902 MHz. The columns in the table portion of Figure 4.1 show, from left to right - the percentage of datapoints that were actually visible from the transmitter and were also in a particular commshed, the percentage of points in the Terrain Only Viewshed that were also in the commshed, and the percentage of points within the Buildings Added Viewshed that were also in the commshed. Figure 4.1 shows that a power margin of 40 dB added to a 28 GHz transmitter will allow the transmitter to reach all points in the TO viewshed, while a power margin of only 10 dB will reach 97% of all points in the BA viewshed. Figure 4.2 shows that a power margin of 40 dB added to a 902 MHz transmitter will allow it to reach all of the points in the TO viewshed, while a power margin of 20 dB will make all of the BA viewshed reachable. Values over 100 in both figures mean that there are more points in the commshed than there are in the viewshed. This means that, for our LMDS frequency, a 40 dB margin will reach at least the area within the Terrain Only viewshed.

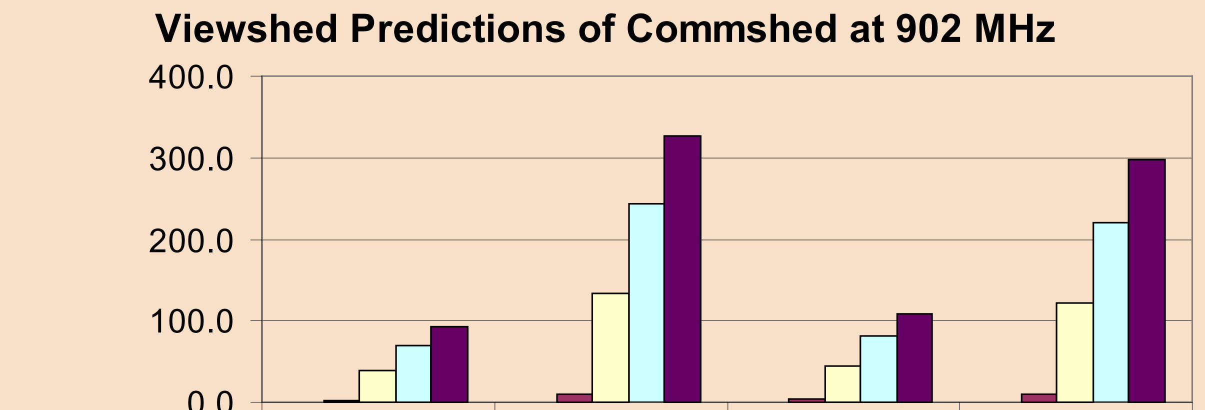
For the 28 GHz commshed, our expectations of fewer points than the viewshed was correct. However, for 902MHz, our hypothesis was proven incorrect. This analysis of viewsheds and radio wave coverages indicates that the BA Viewshed can be used as a prediction model for the LMDS commshed, given a 10dB margin and the TO Viewshed can be used with a 40dB margin. For 902 MHz, a 20dB margin will allow the BA Viewshed to represent the commshed, 40dB again for the TO Viewshed.

Figure 4.1 Commshed Prediction for 28 GHz



	%in ActualView in Commshed	%in TOVwshd in Commshed	%in BAVwshd in Commshed
🟦 Free Space	73.3	24.4	66.7
🟥 10 dB margin	106.7	35.6	97.0
🟨 20 dB margin	173.3	57.8	157.6
⬜ 30 dB margin	253.3	84.4	230.3
🟪 40 dB margin	320.0	106.7	290.9

Figure 4.2 Commshed Prediction for 902 MHz



	%AllData in Commshed	%inActualView in Commshed	%in TOVwshd in Commshed	%in BAVwshd in Commshed
🟦 Free Space	0.0	0.0	0.0	0.0
🟥 10 dB margin	2.9	10.0	3.3	9.1
🟨 20 dB margin	38.1	133.3	44.4	121.2
⬜ 30 dB margin	69.5	243.3	81.1	221.2
🟪 40 dB margin	93.3	326.7	108.9	297.0

Chapter 5. Conclusions

A Geographic Information System allows data to be layered over other data in order to see new patterns across a spatial expanse. This combination can provide input to geoprocessing functions that produce new information about that spatial extent. In this study of the Blacksburg, VA area we used elevation data, building location and height information as input layers for the viewshed function. The new data created were the areas within the study area that the GIS predicted as visible from a particular site. We hypothesized that this new data could be used as a predictive model for areas that could receive data sent from a radio transmitter emitting a signal at a Line-of-Sight frequency.

The spatial analysis of the visibility assignment errors in both viewsheds suggests that the viewshed function would increase its predictive accuracy with an increase in accuracy of the data used for its input. This suggestion is reinforced as we look at the results of the comparison of the commshed predictive accuracy of the two viewsheds.

If the radio system were to be constructed with a power margin of 40dB, then the Terrain-Only Viewshed could be used as a predictive model for general estimations for the radio system. Because of the lack of building data in the viewshed, the accuracy of predicting a particular point’s visibility is not very high. However, predicting the area of a commshed by the viewshed area would allow estimation of the number of people reached in a particular cell and allow for the estimation of the number of transmitters necessary to cover a particular area with complete cellular coverage.

With building height data included in the viewshed model, the viewshed analysis could be used to predict the extent of a LOS commshed with a power threshold of only 10dB. If the radio system was planned with a power margin of 20 dB, the Building Added viewshed could be used as a conservative estimate of the number of people reached by a particular tower. Furthermore, the viewshed could be used to find blind spots in the radio coverage and help in the siting of new towers.

The data collected at 900 MHz were used as a baseline to which the LOS data were compared. This frequency was chosen for comparison because it is a common frequency used in cellular systems and because the Center for Wireless Telecommunications had previously performed tests at that frequency. The data collected at 900 MHz and the resultant commsheds showed that the wavelength acted as expected, bouncing off and bending around buildings. The comparison of the commsheds of the two frequencies showed that the 900 MHz signal was received at a usable level over a larger area than the 24.7 GHz signal. However, comparison of these commsheds to the GIS' visibility predictions revealed that the viewshed function is a more accurate predictor for wavelengths that are near Line-of-Sight frequencies than for longer wavelengths.

Overall, the findings of this study suggest that a GIS' viewshed function can be used as a major component in determining the profitability of establishing a LOS cellular system in a particular area. The viewshed can show the general areas where signals can be received and with the addition of population data, the number of people that can be served by each cell in the proposed system. Furthermore, including building heights in the elevation model produces a more precise commshed, thereby allowing a rough sketch of the layout of transmitter towers to be made. The largest impediment to increasing the predictive accuracy of the viewshed appears to be input data resolution and accuracy. Secondary concerns are the addition of vegetation data and the radio frequency's variance from true Line of Sight activity (possible bends and bounces of the radio wave).

Further research into this topic should include a viewshed analysis for the study area using higher resolution ground and building elevations. The amount of data received at points below, at, and above the threshold value should be examined to better understand the action of LMDS frequencies. More research into the viewshed algorithm could help determine whether the function can be altered to allow prediction of non-LOS frequency commsheds. All of this research is targeted at creating the spatial component of a new geographic-engineering tool for GIS that will enable the user to more easily evaluate, both quickly and cheaply, the viability of implementing an LMDS system for a particular market.

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Appendix A

Error Matrices and KHAT Equations

	BA Viewshed		
ActVw	In	Out	bldgVw
In	22	7	29
Out	9	65	74
	31	72	87
	*X*ii =		87
	N =		103
	*0*1 =		0.844660194
	k hat =		0.62391602
	variance (k hat) =		0.007248345919

	TO Viewshed		
ActVw	In	Out	CmpVw
In	29	0	29
Out	61	13	74
	90	13	42
	*X*ii =		42
	N =		103
	*0*1 =		0.40776699
	k hat =		0.107147932
	variance (k hat) =		0.025760543567
	Z =		1.004136142

Khat equation for BA Viewshed

$$\text{Khat} = \frac{(\,|(CPP / TP)| - ((InActVw * InBldgVw) + (OutActVw * OutBldgVw)) / (TP) * (TP))}{1 - ((InActVw * InBldgVw) + (OutActVw * OutBldgVw)) / (TP) * (TP)}$$

where CPP = correctly predicted points
TP = total points

Z value equation to test for significant difference

$$Z = \frac{|\,KHat_{TO} - KHat_{BA}\,|}{\sqrt{var(KHat_{TO}) + var(KHat_{BA})}}$$

Vita

Howard Mannin Dodd

Mannin Dodd was born on November 3rd, 1970 in Norfolk, Virginia. He graduated from Norfolk Academy in 1988 and attended Mary Washington College in Fredericksburg, Virginia where he received a Bachelor of Arts degree in Geography.

In 1997, while a graduate student in Geography at Virginia Tech in Blacksburg, Virginia, Mannin was offered an assistantship with Tech's Center for Wireless Telecommunications. Working as a GIS Specialist, he helped find communities in the region that were best suited for wireless system implementation and became interested in the correlation between viewsheds and Line of Sight radio waves. After completing his thesis research at the Center for Wireless Telecommunications in 1999, Mannin began working for the U.S. Forest Service's Slow the Spread of the Gypsy Moth Program, located in the Department of Entomology at Virginia Tech. Serving as a Research Specialist, he produced maps that provide information on the number and movement of Gypsy moth in the project area, and worked with the state cooperators to create GIS tools that ease the flow of data from the field to the database and GIS. In the fall of 2001, Mannin received a Master of Science degree in Geography while continuing to work for the Slow the Spread Program.