Canopy, Terrain, and Distance Effects

on Global Positioning System Position Accuracy

by

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(ABSTRACT)

A number of tests were conducted to determine the realizable accuracies of the Global Positioning System for natural resource conditions. The effects of terrain, forest canopy, number of consecutive position fixes, and PDOP on accuracy were evaluated. Position accuracies were determined for a total of 27 sites: three replicate sites selected for each of nine distinct conditions: three canopy (deciduous, coniferous, open) and three terrain (ridge, slope, valley) in all possible combinations. Each site was visited ten times over a span of eight months to collect position data, for ten replicates of 60, 100, 200, 300, and 500 position fixes.

The mean differentially corrected positional accuracy for all sites was 4.35 meters with 95 percent of the positions estimated within 10.2 meters of the true value. The least accurate differential position data were observed at coniferous sites. Positional accuracy was higher for deciduous sites and the most accurate differential position data was collected at open sites.

Accuracy increased with increasing number of position fixes. When the number of position fixes increased from 60 to 500, mean accuracy increased 46.7% at deciduous sites, 32.8% at coniferous sites, and 44.5% at open sites.

The average time required by the GPS receiver to lock onto four satellites and begin collecting positions varied from one to two minutes. The most time was spent collecting position fixes at coniferous sites.

No correlation was found between accuracy and the receiver's distance from the base-station. Nine replicates of 300 position fixes were averaged for six sites, which ranged from 43 kilometers to 247 kilometers from a Virginia Tech base-station. Mean accuracy ranged from 1.48 meters to 2.43 meters.

GPS position data were evaluated for ease of conversion to GIS formats. Conversion was accomplished without problems.

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Introduction

Many resource management organizations are interested in improving the quality of their geographic information, and Global Positioning System (GPS) technology is rapidly providing a means to acquire timely and accurate spatial data. The range of applications for GPS technology seems to be limited only by the imagination. For example, investigations by the USDA Forest Service GPS Steering Committee cited over 130 applications of GPS, including locating and mapping timber cruise plots, roads, and trails (Kruczynski and Jasumback 1993). The National Park Service (NPS) applies GPS to fire, law enforcement, trail, and cultural resource mapping (NPS GIS Sourcebook 1993). The Environmental Protection Agency (EPA) plans to apply GPS to mapping natural spatial features such as "air, water, and biological natural resources and their environmental stressors" as well as the many other features present at EPA site investigations (Slonecker and Groskinsky 1993).

With this heightened need for accurate spatial data and the use of GPS for its acquisition, there is a need to understand the accuracies achievable in forested landscapes.

Objectives:

The purpose of this research was to evaluate GPS use and aid in the evaluation, selection, and use of appropriate GPS technology. The objectives of this study were:

1) Determination of the effect of satellite geometry, forest canopy, and terrain interference on realizable accuracies while evaluating the performance of inexpensive (C/A code) receivers under operational conditions.

2) Evaluation of the effect of distance from the base-station on the accuracy of differentially corrected position data.

3) Assessment of the appropriateness and limitations of GPS for GIS data layer development.

Literature Review

The Global Positioning System:

The Coast Guard GPS Informational Center (CGGPSIC) states:

> "The NAVSTAR Global Positioning System is a space-based radio positioning system which provides suitably equipped users with highly accurate position, velocity and time data. When fully operational, this service will be provided globally, continuously, and under all weather conditions to users at or near the surface of the earth. GPS receivers operate passively, thus allowing an unlimited amount of simultaneous users."

The GPS was developed by the Department of Defense (DOD) to simplify and ensure accurate navigational information. The CGGPSIC continues:

> "The GPS comprises three major segments, space, control, and user. The space segment consists of a constellation of GPS satellites in semi-synchronous orbits around the earth. Each satellite broadcasts radio-frequency (RF) ranging codes and a navigational message. The GPS space segment, when fully operational, will consist of 21 operational satellites. The satellites will complete an orbit in approximately 12 hours. The control segment consists of one master control station (MCS) at Falcon AFS in Colorado Springs, USA, plus monitor stations at the MCS and four other locations around the world. The MCS is responsible for tracking, monitoring, and managing the satellite constellation and for updating the navigational data messages. The user segment consists of a variety of military and civilian radio navigation receivers specifically designed to receive, decode, and process the GPS satellite ranging codes and navigation data messages. They include stand-alone receiver sets, as well as equipment that is integrated with or embedded into other systems.

> Consequently, GPS receivers for different applications can vary significantly in design and function."

The NAVSTAR satellites orbit the earth at approximately 11,000 nautical miles and transmit two L-band radio frequencies. The two carrier signal frequencies, 1227.6 Mhz and 1575.42 Mhz, are modulated by the Precise or Protected code (P-code) and the Course/Acquisition code (C/A code) often called the civilian access code (Hurn 1989). The P-code is most often used for high accuracy surveys.

Most inexpensive, civilian GPS receivers utilize the "pseudo-random" code transmitted on the carrier signal from the GPS satellites. Those (C/A) mode receivers use the pseudo-random code to determine distance to each satellite. Distances from four satellites, combined with broadcast satellite position information, allows 3-dimensional position determination.

Other forms of GPS positioning utilize the carrier signal itself for very accurate time resolution. These "carrier phase" techniques generally require longer uninterrupted signals and suffer under closed forest canopies. However, where applicable, carrier phase data may yield accuracies of better than a few centimeters.

Positional Accuracy:

GPS positional accuracy depends on many factors (Liu 1993). Selective Availability (SA), implemented by the DOD, degrades the accuracy of the positions by deliberately introducing errors into the satellite navigational data and clock. SA, when enabled, decreases positional accuracy to 30 meters (m) or more. Errors in the satellite clock, the satellite ephemeris, and the receiver clock all degrade accuracy at the meter level. Ephemeris data are transmitted by each satellite and are used by the receiver to predict the satellite position. Atmospheric delays of the radio signal affect positional accuracy from 1 to 3 meters. Table 1 summarizes the causes of error (Bolstad 1993, Hurn 1989, Milliken 1980).

Position Dilution of Precision (PDOP) is a measure of the positional accuracy with respect to latitude, longitude, and altitude. PDOP is a numerical representation of the geometry of the satellite constellation. An ideal configuration of the satellites for 3-dimensional positioning would consist of one satellite directly overhead and three other satellites equidistant and just above the planar horizon. The lower the PDOP, on a scale of 1 to greater than 100, the higher the positional accuracy (Wells 1986). One rule of thumb for estimating accuracy is to multiply the PDOP by the sum of

Table 1. Predicted GPS accuracy under autonomous conditions.

Error Source	**Expected Autonomous Accuracy**
Satellite Clock Receiver Clock	0.5 meters - 1.0 meter 1.0 meter - 1.5 meters
Ephemeris	0.5 meters - 1.0 meter
Ionosphere	3.0 meters - 4.0 meters
Selective Availability	0.0 meters - 100 meters
Accuracy Totals	5.0 meters - >100 meters

possible errors; giving a rough estimate of expected positional accuracy (Hurn 1989). For example, if errors from Table 1 total 5 m and the PDOP is 4, then the expected accuracy is approximately 20 m.

Positioning that includes errors from the satellite and receiver clock, the atmosphere and ionosphere, receiver noise, and SA is referred to as autonomous positioning. Autonomous positioning usually results in horizontal position accuracies of 10 to 100 meters.

Differential positioning with correction provides increased accuracy. Differential positioning utilizes two GPS receivers, one (base) receiver stationed over a known point and another receiver (rover) over unknown points. The two receivers collect data simultaneously, from the same set of satellites ensuring that errors with respect to satellites, system delays, atmosphere, and SA are similar for each receiver. Differential corrections do not remove the effects of PDOP. The base-station is referenced with its actual position and a correction vector is computed. The correction vector is then applied to position data collected by the rover, yielding corrected positions. Differential correction using the mean of 100 to 300 consecutive position fixes in areas that are free of obstructions yield accuracies in the 2.1 to 3.4 meter range (August et. al. 1994).

Elevation masks define the minimum acceptable satellite elevation angle. The elevation mask screens the use of satellites near the planar horizon, thereby reducing the effect of long atmospheric path length on the satellite radio signal. The elevation mask also helps ensure that the base-station and field receiver are scanning the same areas of the sky for the same sets of satellites. Elevation masks may be used to reduce the chance of multipath occurring. Multipath, which is not removed by differential correction, is the reflection of satellite signals from objects near the antenna.

Most GPS units compute coordinates using the World Geodetic System of 1984 (WGS-84) datum. The WGS-84 coordinates can then be transformed to other coordinate systems as desired. The vertical coordinate is usually measured as either elevation above mean sea level (MSL) or height above ellipsoid (HAE).

GPS Use in Natural Resource Management:

Because GPS is significantly affecting all parts of spatial information collection, natural resource measurements and management will forever be altered. GPS may aid natural resource researchers and managers in many activities which require position or area measurements. Most previous GPS evaluations, however, have been performed under "clear sky" conditions, where views to satellites are unobstructed by vegetation or terrain (August et. al. 1994). Therefore, there are many questions regarding the capabilities and limitations of GPS technology in natural resource settings. Uncertainties include realizable accuracies, the nature of forest canopy interference, measurement efficiencies, user requirements, and how GPS technology might best be integrated into current data collection protocols.

Although many people have been using GPS in forested situations of late, only a few studies have documented forest canopy effects on accuracy. Gerlach (1989) focused research on the effects of lodgepole pine (pinus contorta) trunks, branches and foliage on positional accuracy. Gerlach (1989) found that the loss of the radio signal from the satellite was caused 23% of the time by the trunks, 28% by branches, and 36% by the foliage. Autonomous collection under the lodgepole pine canopy yielded an average difference between the actual position and the GPS acquired position of 6.5 meter (m) North-South (N-S) and 5.2 m East-West (E-W). The differentially corrected field positions averaged a N-S displacement of 3 m and a E-W displacement of 4 m. Evans (1992) focused research on the navigation abilities of GPS to locate forest plot centers. The average autonomous displacement of the GPS position to the actual plot center was 2.01 m. The high accuracy of the autonomous positions in these two studies was because SA was inactive. Today SA is constantly active and severely affects autonomous positional accuracy.

Tests of GPS efficiencies in the dense rain forests of northeastern Zaire, Africa experienced quite long times to the first 3-dimensional position fix. Position determination was obtained within 20 minutes in areas where elevation angle was less than 50 degrees, canopy closure was less than 20 percent, and there was a forest opening of > 0.125 ha (Wilkie 1989).

Methods

Goal 1 - Realizable Accuracies:

Accuracy in this thesis refers to the horizontal distance from the GPS acquired positions to the actual surveyed site positions. Realizable accuracies were determined from GPS measurements over precisely surveyed points. Coordinates for forested sites were determined by one of two methods. First and second order National Geodetic Survey (NGS) markers were located within Shenandoah National Park (SNP) and in the vicinity of Blacksburg, VA. Using a transit and stadia, according to methods described in Wilson (1990), traverses were established to locate the exact position of points at sites with desired forest type and terrain near the NGS marker. Traverses from the NGS marker to the forested sites had an average error of closure of 0.58 m and a maximum error of closure of 0.899 m. Five forested sites were surveyed from NGS markers.

Because most NGS markers are on ridge-tops, another method was needed to set up sites in forests located on slopes and in valleys. Carrier phase differential positioning was the second method used to locate highly accurate positions far from NGS markers. Our tests (with the Magellan 5000 Pro sub-meter kit) using paired first order NGS markers resulted in an average horizontal error under 20 centimeters.

Carrier phase positions were established in clear areas adjacent to desired forested sites. Once the carrier phase point was obtained, traditional survey traverses were used to establish forested sites. Thirteen forested sites were surveyed from carrier phase points. Figures 1 and 2 show the distribution of sites around the base-stations.

The open sites were also located on the three terrain types. The three open sites on ridge-tops were established on NGS markers. The six remaining open sites were established using carrier phase techniques. Please refer to the Appendix for detailed information on individual sites.

Oaks (quercus spp.) were the dominant tree species at the deciduous sites. Conifer sites were usually single species stands of eastern hemlock (tsuga canadensis), red cedar (juniperus virginiana), or virginia pine (pinus virginiana). Deciduous and coniferous sites were assessed for basal area per acre with a 10 BAF prism. The basal area for deciduous sites ranged from 80 ft^2/acre to 140 ft^2/acre and averaged 100 ft^2/acre. The basal area at conifer sites ranged from 80 ft^2/acre to 240 ft^2/acre and averaged 133 ft^2/acre. Using a canopy densiometer, the deciduous and coniferous sites both

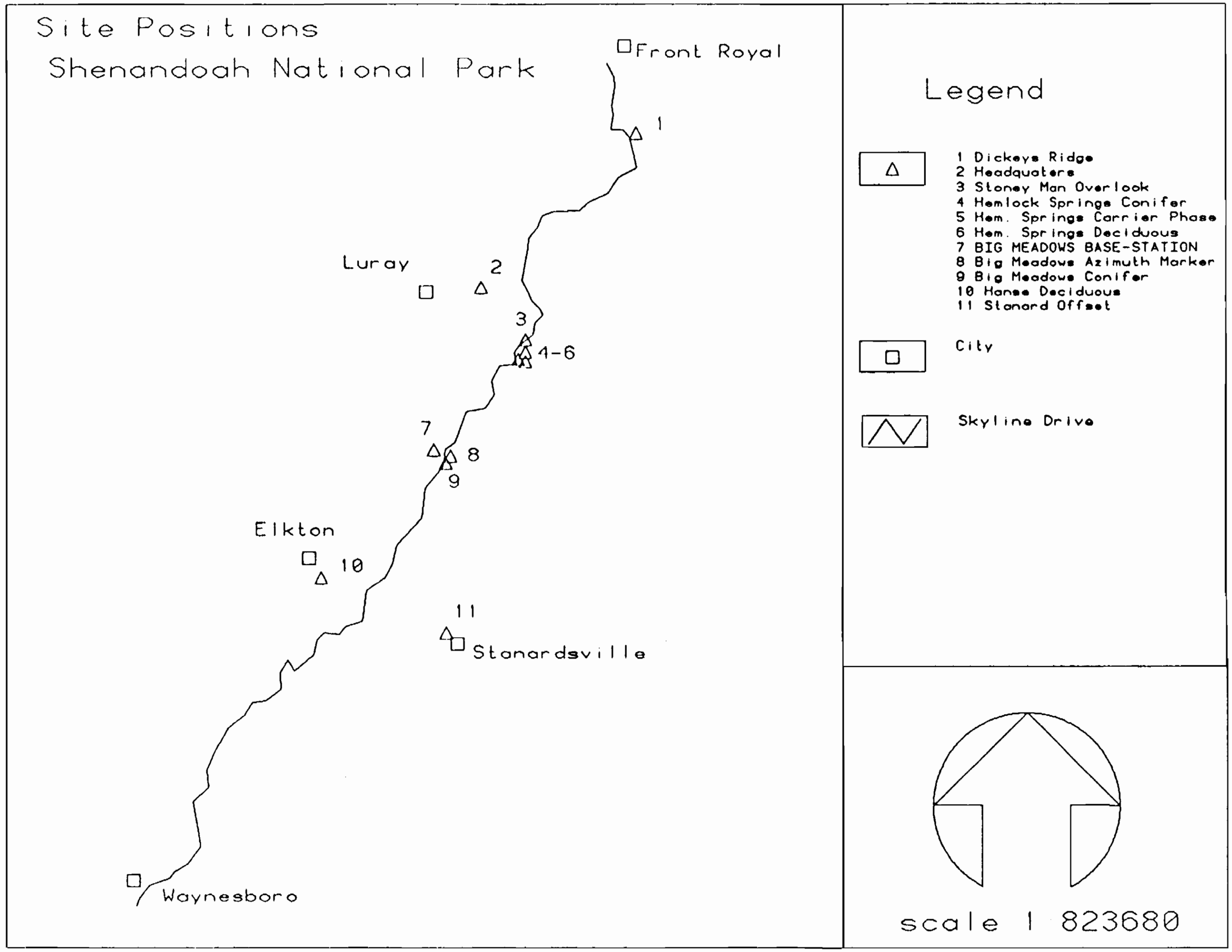

Figure 1. The position of all the sites found in Shenandoah National Park with respect to the Big Meadows base-station. The points ranged from 1.14 km to 41.96 km from the base-station.

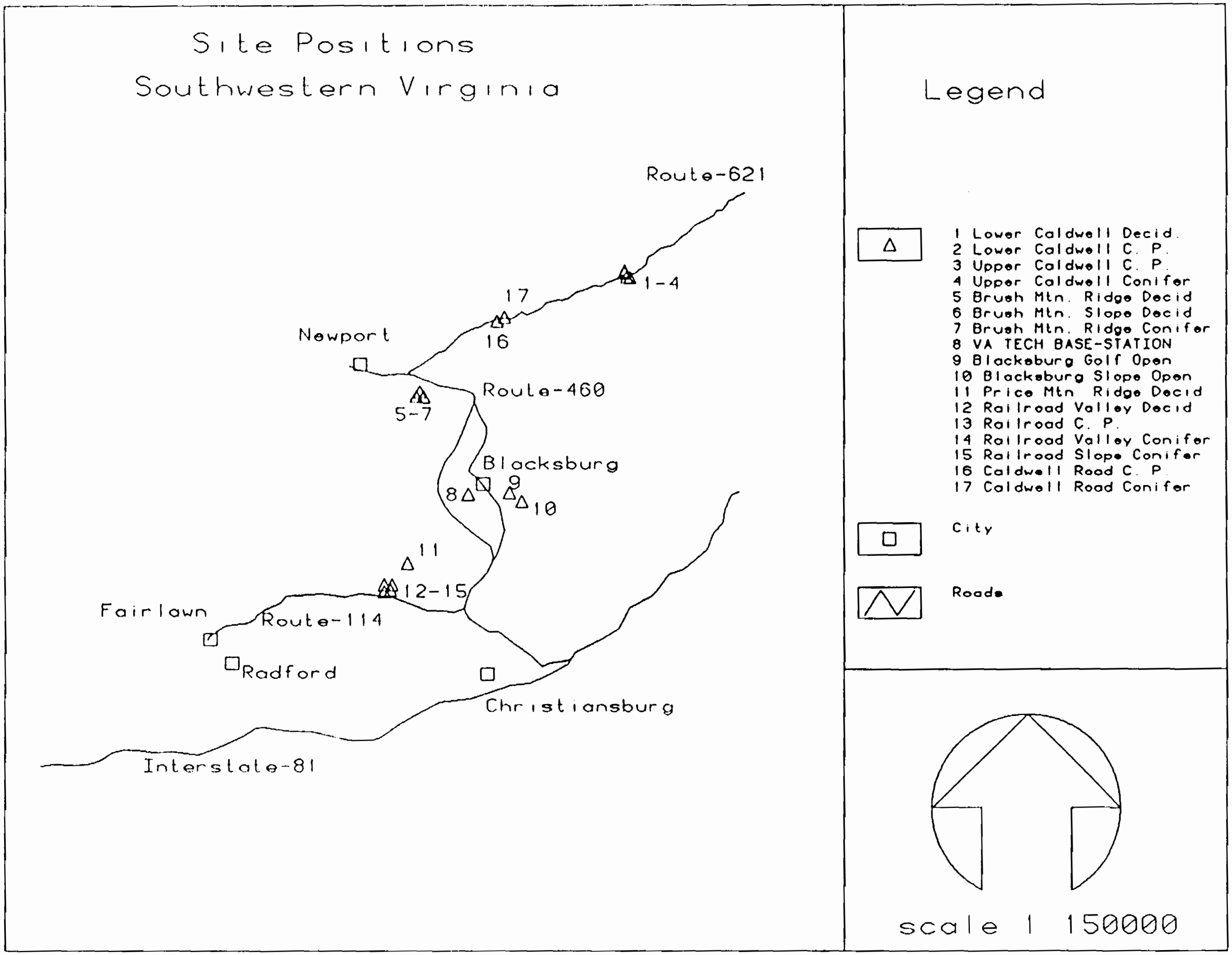

Figure 2. All the sites found in the Blacksburg, Virginia vicinity with respect to the Virginia Tech base-station. Distances ranged from 2.41 km to 15.41 km.

height was 20 meters and the forests surrounding all the sites were at least 50 years old. The coniferous and deciduous sites in this study represent the worst case scenario for GPS position collection in naturally occurring eastern U.S.A. forests. It is likely that the positional accuracies would continuously increase as the forest density and canopy closure decreases, approaching the accuracies attainable at open sites.

The terrain elevation above the horizon surrounding each site was determined by use of a clinometer. Terrain obstructions of the sky averaged 2 degrees above the horizon for ridge sites, 20 degrees for slope sites, and 19 degrees for valley sites. Ridge sites were characterized by clinometer readings of 0 to 5 degrees above the horizon in all directions about the sites. Slope site clinometer readings ranged between 14 and 31 degrees above the horizon up slope from the site and downslope the clinometer readings were just a few degrees above the horizon. The valley sites were blocked by terrain on at least two sides with the slopes ranging from 11 to 37 degrees above the horizon.

Position data were collected with a Trimble Pathfinder Professional connected to a Corvallis Microtechnology MC-V datalogger. All work in the Blacksburg area used a Trimble Community Base-Station (CBS) for differential correction. Data collected in SNP utilized a Trimble Pathfinder

Professional for the base-station. Both base-stations were 6-channel receivers. The coordinates for the SNP base-station were determined by a park surveyor using third order techniques and a short (< 1 km) baseline. The antenna was located at the top of a 11 meter tower for a clear, 360 degree view of the sky. The field and base-station receivers were both set with an elevation mask of 15 degrees above the planar horizon. The field receivers were set with a PDOP mask of 11 and was set to search for a better constellation of satellites if the PDOP reached eight. Minimum satellite signal strength was set at six, with a logging rate for the field receiver of one position record every second. Collection of satellite data on the MC-V utilized the CMT-ROS 2.06T operating system and Pathlog 1.59 04/08/92 software. Analysis of receiver data was performed by Pathfinder Professional Post-Processing Utilities PFINDER 2.10-24 April 1992. All data collected at forested and open sites were recorded using the manual 3-dimensional mode. Receivers were set to record coordinates based on the WGS-84 geodetic datum and HAE.

Data Collection:

Accuracies of both autonomous and differentially corrected data were determined. Ten visits (replicates) were made to each site over a span of eight months to ensure a wide range of conditions and PDOPs. Since multiple observations (from 60 to 500) were available from each visit to each site, the variance and statistical distribution about the mean were determined. Determination of the bias (average accuracy), variation, and statistical distribution of both autonomous and differential positioning were performed. A range of PDOPs was collected at each site. Single receiver operation was expected to be most affected by Selective Availability, while differential accuracies were expected to be most sensitive to PDOP.

In order to assess collection efficiencies, time to first position fix and speed for each subsequent position fix were recorded and summarized.

Canopy type and terrain effects were determined through measurements over a range of conditions for canopy, terrain, and satellite geometry. Canopy in this thesis refers to the type of overstory and forest surrounding the site. The sites consisted of three terrain types (ridge-top, slope, and valley) and two forest types (deciduous and conifer). Each combination was replicated three times for a total of 18 forested sites. The sites were clustered in two areas of southwestern and western Virginia, one in SNP and the other near the town of Blacksburg, Virginia. Nine open canopy sites, three for each of the ridge-top, slope, and valley terrain types were established for comparison to the forested sites. The open sites were also used to evaluate the reduction in accuracies due to canopy attenuation of the satellite radio signal.

Collection of the deciduous forested data spanned May 1993 through September 1993. Conifer data collection took place from May 1993 through January 1994. The data for open canopy sites were collected from November 1993 to January 1994.

Five files were created on the MC-V at each visit to a site, one for each number of position fixes; 60, 100, 200, 300, and 500. Each file took approximately one minute for the MC-V to set up. Including receiver set up and take down each visit required approximately one hour to complete. Over 1300 files were created from May 1993 through January 1994.

A number of variables were recorded for each file. For clarity a file naming convention was required to keep track of the over 1300 files. The file naming convention used a key which included the date, position number, and the number of position fixes in the file. In order to assess effects of canopy and terrain on satellite acquisition, the time to lock onto four satellites and compute the initial position fix was recorded. Because each file represented a pre-determined number of position fixes, total time required to collect the position fixes indicated the loss of lock due to some external inhibitor. For example, 60 position fixes should take one minute to collect. Any collection time over one minute would indicate a loss of satellites for 3-dimensional positioning.

The Pathlog software did not display the cumulative number of position fixes while doing data collection. However, the software may be set to beep every time a position fix is calculated, therefore the beeps were recorded in order to collect approximately the correct number of position fixes for the file. The version of the Pathfinder software used during this study did not record PDOP, therefore PDOP was recorded during the collection of the position fixes. For the files that took more than a few minutes to record the PDOP often changed during the session, up to 15 times for a 500 position fix collection. Each PDOP that occurred during the session was recorded.

Post-Processing:

The data were downloaded onto a computer and analysis with Trimble software produced information for individual field files. Information on the following variables was produced. The Universal Time Coordinated (UTC) was recorded in order to obtain the corresponding base-station data. The base-station used to differentially correct the position data was also recorded. The actual number of position fixes in the file was recorded from the statistics file to ensure that the correct number of beeps were counted. The number of position fixes that were differentially corrected by the base-station was recorded to check consistency with number of fixes and confirm that the base-station and field receiver used the same satellites.

The Virginia State Plane Coordinate System (SPCS), based on NAD-83, was used to record the true position and the mean position from each file. The SPCS is a map grid system that covers the state of Virginia in two zones. Shenandoah National Park is in the north zone (State Plane Zone #4501) while Blacksburg is in the south zone (State Plane Zone #4502). State Plane coordinates were used in calculating, by the pythagorean method, the difference between the GPS receiver position and the actual coordinates.

Analysis:

True and GPS estimated coordinate data were entered into a spreadsheet to produce tables of the autonomous and differentially corrected data. The filename, mean PDOP, terrain, forest type, and actual autonomous and corrected positional accuracy were transferred onto a mainframe computer for statistical analysis using the SAS statistical package.

This thesis reports summary data for the average and distribution of accuracies. These data produced accuracy estimates over the range of conditions expected in southern appalachian forest conditions, and also identified the relative importance of canopy and terrain on accuracy. For example, relative contribution may be determined from analyses of variance (ANOVA) with a dependent variable accuracy and independent variables of canopy type (conifer/ deciduous/ open) and terrain position (ridge-top /slope /valley).

Analysis of Covariance (ANACOVA) was applied to the data. The ANACOVA is similar to an ANOVA but incorporates a continuous variable into the model for ANOVA and regression type output. The ANACOVA test determines which variables are affecting the dependent variable. In our case PDOP was the continuous variable.

Tukey's Studentized Range test was utilized to test for differences among means. In a Tukey's test, the means are ranked from lowest to highest and then pairwise comparisons are made among the means. Statistically similar means may then be identified. For example, a group of means is ranked:

12 10 7 3.5 3

In order to group the means, the sample size, mean square within, the number of means, and the degrees of freedom are needed to produce the formula:

$$W=q_{\alpha}(t,v)\sqrt{(\frac{s_W^2}{n})}$$

where,

s^2_W = mean quare within the samples
q_α = upper-tail critical value
t = number of populations
v = degrees of freedom
n = number of observations
α = 0.05 for this study

The absolute value of the difference between each mean must be less than W to be statistically similar. Underlines then denote which means are different and similar. Given the following format, 12, 10 and 7 would be statistically similar while they are significantly different from 3.5 and 3.

<u>12 10 7</u> <u>3.5 3</u>

The test controls the type I experimentwise error rate. The actual results of the Tukey test are reported in the results without the use of the underlines.

Goal 2 - Distance from Base-Station Accuracies:

In order to differentially correct field data the base-station and the field receiver must both record data from the same constellation of satellites simultaneously. The probability of using different satellites increases as the field receiver is farther from the base-station. Positional accuracy also decreases as a function of increasing distance from the base-station. Accuracy can be affected up to 10 parts per million (ppm). This is a decrease in accuracy of 0.1 meters for every 10 kilometers in rover to base-station distance (Gilbert 1994).

Six NGS points were located at distances between 43 and 237 kilometers from the Virginia Tech base-station. Collections at each site were under optimal conditions, with clear views to satellites and a maximum allowable PDOP of 4.0. Each site was visited nine times to collect five minutes of 3-dimensional position fixes (approx. 300 position fixes). Accuracy as a function of distance was then evaluated.

Goal 3 - GIS Input:

Goal three was accomplished by field data collection and office verification of GIS data entry via GPS. The vendor provided software has a number of GIS export formats. A field sampled area was converted to a GIS data layer format currently being used at SNP. Point location after conversion was verified. Conversion ease was then assessed.

RESULTS AND DISCUSSION

Receiver Accuracies and Efficiencies

Due to missing data the sample size was 1348, two less than the full sample size of 1350. The missing data were to have been from one deciduous slope site and one deciduous ridge site both with 100 position fixes. Because of the large total sample size this loss of data was deemed negligible. The missing data were the result of being unable to differentially correct position data. Since it was late in the season we were unable to return and collect more positions while leaves were still on the trees.

Position Dilution of Precision:

Because PDOP is a result of the configuration of the satellites, it is a variable that is common to both differential and autonomous position data. The PDOPs for the full sample size ranged from 2.6 to 10.7. The mean PDOP for all the sites was 4.97 with a standard deviation of 1.69. The 95 and 90 percentiles were 8.35 and 7.2 respectively. A breakdown of PDOP by forest and terrain type is found in Table 2. Tukey's standardized range test found the mean PDOPs for each canopy type were statistically different at the $\alpha = 0.05$

Table 2. Mean PDOPs for each forest and terrain type combination. Each combination represents a sample size of 150: three sites visited 10 times and five PDOP readings taken at each visit.

Terrain	Canopy Type		
	Deciduous Sites	Conifer Sites	Open Sites
Ridge	4.68	5.29	3.91
Slope	5.20	5.61	4.60
Valley	5.40	5.99	4.02

level. This suggests that the denser canopies caused the receivers to choose a less than optimal set of satellites with a poorer PDOP than could be attained in the less dense canopies. The best PDOPs were observed at open sites. The mean PDOPs at deciduous sites were better than those observed at coniferous sites. The affect of observed PDOPs on autonomous and differential positional accuracy will be discussed later.

Differential Positional Accuracy:

Differentially corrected position data are the most accurate form of code-phase GPS horizontal position information. Because differential correction removes the errors due to Selective Availability the resulting positional data should only be affected by the variables common at all sites. The variables of terrain, forest type, the number of position fixes, and PDOP should be the major factors which affect accuracy.

The mean differential positional accuracy was 4.35 m for all forest types, terrain types, and number of position fixes. Ninety-five percent of the differential position data were in error by less than 10.2 m, and 90 percent by less than 7.95 m. The spread of differential position data with respect to PDOP is shown in figure 3. There are three outliers between 30 and 40 meters. These may be due to multipath effects, which can cause reductions in accuracy. Only six observations were greater than 20 meters. As the results will show later, although PDOP does affect differential position data in this study, the decrease in accuracy caused by PDOP is not major.

The ANACOVA revealed that forest type, terrain type, PDOP, and the number of position fixes all significantly affect differentially corrected GPS positional accuracy at the $\alpha = 0.05$ level. Terrain and canopy, however, were shown to interact with each other and with PDOP. An interaction indicates that accuracy is affected differently for each terrain, canopy and PDOP combination. An ANOVA for PDOP indicated that forest type and terrain significantly affect PDOP. Further analysis using Tukey's Studentized Range test showed a significant difference and increase among the PDOPs when terrain went from ridge to slope to valley.

Regression analysis produces R^2 values which indicate the proportion of the variability in the dependent variable that is accounted for in the independent variables. The lowest R^2 resulted from the terrain affects on differential position variability. The best R^2 value from an individual variable resulted from the analysis of canopy type and was 0.106. When the full model of variables and all their combinations is used

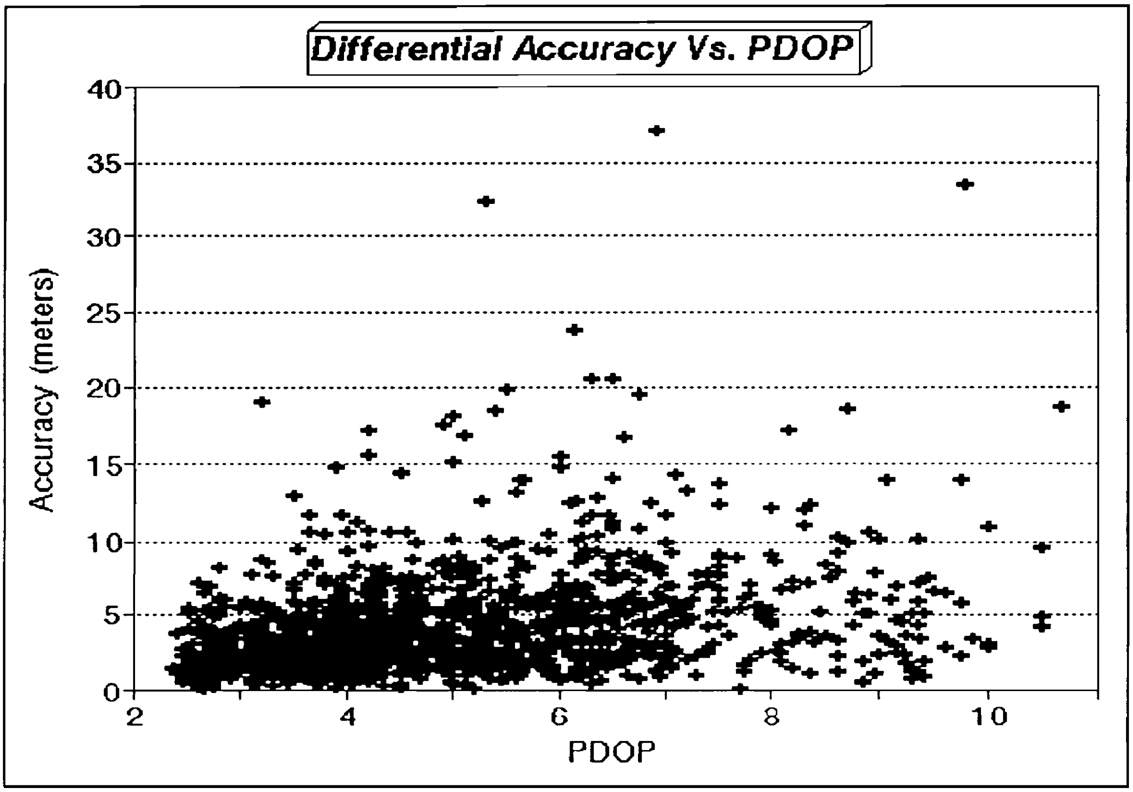

Figure 3. All differentially corrected position data with respect to PDOP.

the R^2 value is 0.253 (Table 3). The observed variation of the differential position data must be due to other sources such as multipath.

The terrain effects on differential positional accuracy were different for the three forest types. Tukey's Studentized range test for open sites found mean positional accuracy at ridge sites to be significantly different from slope and valley sites. The slope and valley sites were statistically similar. Terrain was not a significant factor at deciduous sites. Mean accuracy for ridge and valley sites in coniferous forests were statistically different while slope sites were similar to both ridge and valley sites. Therefore, at coniferous sites, there was a gradual decrease in accuracy from ridge-tops to valleys.

The accuracy for each terrain and canopy combination is shown in figure 4. The graphs show that there are differences in accuracy among the three canopy types. Figure 4c shows little distinction between ridge-top deciduous and coniferous forest type. The deciduous and open canopy types are similar in accuracy but different from the coniferous canopy at the valley and mid-slope sites (Figures 4a and 4b).

The number of position fixes collected at a site played a major role in improving accuracy (Table 4). Accuracy of mean positions increased approximately 47% at deciduous sites,

Table 3. The R-Squared resulting from regression analysis of individual variable affects and the full variable model on differential position accuracy.

	Differential Accuracy R^2
PDOP	0.089
Number of Position Fixes	0.054
Terrain	0.008
Canopy	0.106
Full Model with all Variables	0.253

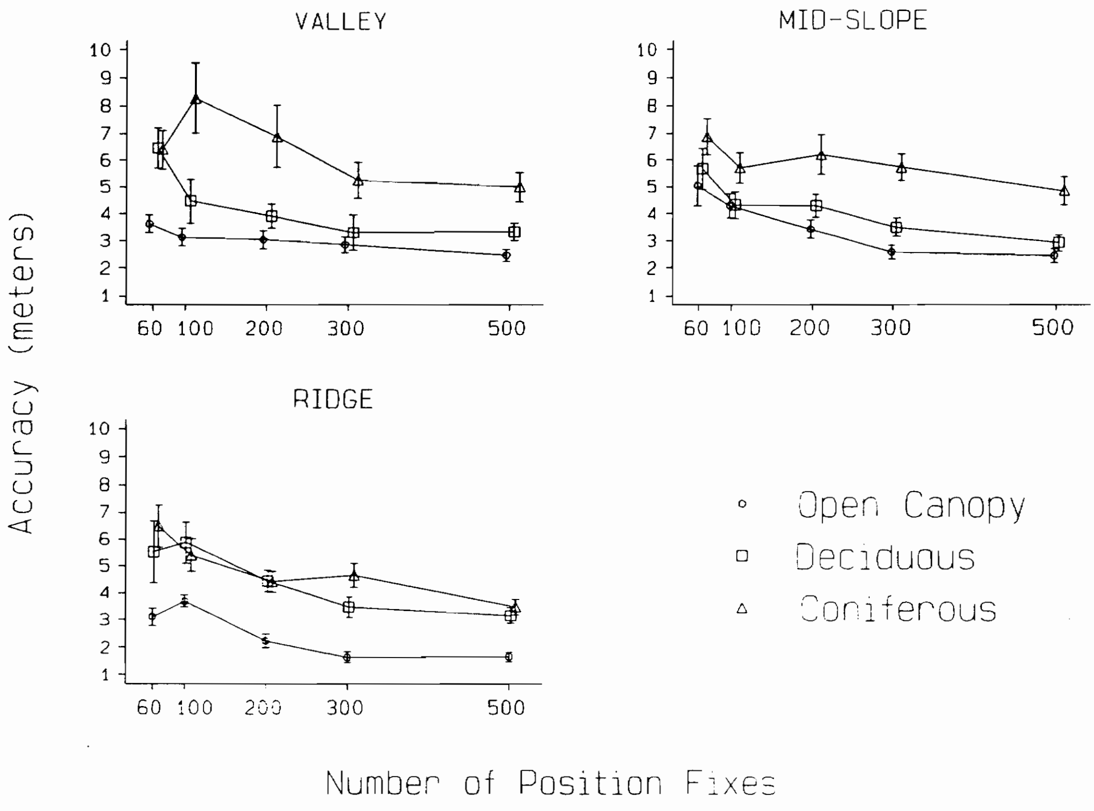

Figure 4. Accuracy of position fixes for each canopy type with respect to individual terrain types. Each point represents 30 site visits: three separate sites replicated for 10 visits each.

Table 4. The differential position accuracy for each forest type and each number of position fixes. The sample size was 90: nine sites for each forest type visited ten times. The 90th and 95th percentiles are shown under each mean.

Mean 90th Percentile 95th Percentile	Forest Type		
Number of Position Fixes	Deciduous Sites (meters)	Conifer Sites (meters)	Open Sites (meters)
60	5.89 10.77 15.53	6.59 12.11 14.54	3.93 6.74 7.82
100	4.88 9.93 11.02	6.46 11.76 14.05	3.53 6.55 7.46
200	4.21 7.27 8.68	5.83 10.33 14.01	2.89 5.98 6.26
300	3.76 6.17 7.71	5.20 8.30 10.34	2.36 4.64 5.31
500	3.14 5.47 6.25	4.43 8.45 10.64	2.18 3.85 4.48

from 5.89 m for 60 position fixes to 3.14 m for 500 position fixes. The increase in mean positional accuracy was the greatest at deciduous sites. Mean positional accuracy for coniferous sites increased the least of the three canopy types: 33%, from 6.59 m for 60 position fixes to 4.43 m for 500 position fixes. Open site positional accuracy increased 44%, from 3.93 m at 60 position fixes to 2.18 m for 500 position fixes.

Tukey's Studentized Range Test was applied to each canopy type in order to detect if there were any differences among the number of position fixes at the $\alpha = 0.05$ level. For deciduous sites 60 and 100 position fixes are similar, 100, 200, and 300 are similar, and 200, 300, and 500 are statistically similar. Coniferous sites were similar at 60, 100, 200, and 300 position fixes and at 200, 300, and 500 position fixes. Groups of similar means for the open sites include 60 and 100 position fixes, 100 and 200 position fixes, and 200, 300, and 500 position fixes. There is not a distinct difference among the means for each forest type, indicating a gradual increase in accuracy from 60 to 500 position fixes. The accuracy achieved for 200 position fixes is statistically similar to that for 500 position fixes for each canopy type.

In order to collect accurate positional data, differential correction is essential. Differential correction was attempted on a total of 1487 files collected under the diverse conditions in this study. Of the 1487 attempts at differential correction, 1392 of the files were successfully corrected. The success rate was therefore 93.6%. The cause for most of the failed differential corrections was due to the receiver and the base-station using different satellites. The base-stations used in this study were 6-channel receivers. 12-Channel "all in view" base-stations are now available, which should greatly reduce the likelihood of the field receivers and the base-station using different satellites.

Autonomous Positional Accuracy:

The Autonomous position accuracies ranged from 0.05 m to 178.43 m. The mean autonomous accuracy was 31.28 m with the 95 percentile 79.42 m and the 90 percentile 64.80 m. Although the mean may be adequate for some applications, the percentiles show that the range of the data is quite large. The full range of autonomous data with corresponding PDOPs is shown in Figure 5.

The ANACOVA results show that there is terrain, canopy type, and PDOP interaction. The variables that significantly affect autonomous positional accuracy at the $\alpha = 0.05$ level are canopy type, PDOP, and the number of position fixes.

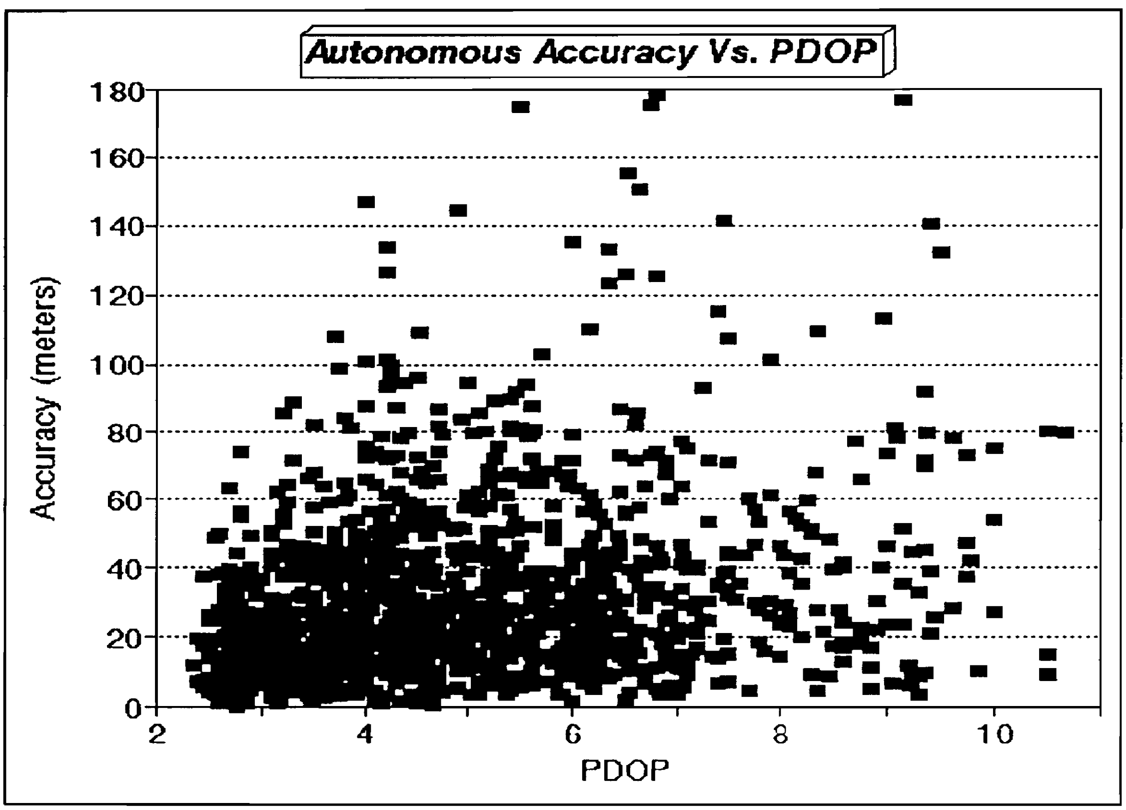

Figure 5. Autonomous position data for all forest types, terrain types, and all position fixes.

A regression model of all possible variable combinations yielded an R^2 of 0.197.

Autonomous positional accuracies were statistically similar for both the deciduous and coniferous sites. This is most likely due the effect of Selective Availability causing high variability in the positional data which masks most of the other factors affecting positional accuracy. Positional accuracy improved as a result of the increased number of position fixes (Table 5). Mean positional accuracy at deciduous and coniferous sites improved 47% and 46% respectively from 60 position fixes to 500 position fixes. Mean autonomous positional accuracy for open sites increased 32% from 29.24 m for 60 position fixes to 19.79 m for 500 position fixes.

The Tukey standardized range test revealed that autonomous positional accuracy at deciduous sites was similar for 60, 100, and 200 positions, 200 and 300 position fixes were similar, and that 300 and 500 position fixes were statistically similar at the $\alpha = 0.05$ level. The open sites were statistically similar for 60, 100, 200, and 300 position fixes and 100, 200, 300, and 500 position fixes. Means of autonomous positional accuracy for each number of position fixes at conifer sites were combined in three statistically similar groups: 60, 100, and 200 position fixes, 100, 200, and 300 position fixes, and 300 and 500 position fixes.

Table 5. The autonomous position accuracy for each forest type and each number of position fixes. The sample size was 90: nine sites for each forest type visited ten times. The 90th and 95th percentiles are shown under each mean.

Mean 90th Percentile 95th Percentile	Forest Type		
Number of Position Fixes	Deciduous Sites (meters)	Conifer Sites (meters)	Open Sites (meters)
60	44.38 88.89 101.66	41.03 89.60 126.04	29.24 58.41 65.04
100	40.99 79.80 89.23	42.34 80.85 101.68	28.19 57.11 69.83
200	34.31 67.33 73.73	32.93 72.67 82.53	26.79 61.05 73.81
300	28.43 57.99 79.76	32.01 60.58 72.97	23.02 46.51 67.40
500	23.51 43.84 52.97	22.26 39.76 45.68	19.79 41.92 52.47

As with the differential data, no distinct separation is made among the groups. There is a gradual increase in accuracy for each canopy type as the number of position fixes increases.

Position Collection Times:

An important consideration for resource managers is the time spent collecting field data. The ANACOVA results show that, as was expected, the number of position fixes significantly affected collection times at a site, as well as the terrain and canopy. PDOP did not significantly affect collection time. The full model with all variable combinations produced an R^2 of 0.5. This high R^2 value results from the high dependency of collection time on the number of position fixes collected, which alone produces an R^2 value of 0.4.

Collection times differed greatly among the three canopy types (Table 6). Collection times for 500 position fixes ranged from 8.82 minutes at open sites to 14.23 minutes at conifer sites. That is an increase of one position fix every 1.06 seconds at open sites to one position fix every 1.71 seconds at conifer sites. The mean number of seconds to collect one position fix for open, deciduous, and coniferous sites were 1.08 seconds, 1.52 seconds, and 2.05 seconds respectively.

The time required to collect 60 and 100 position fixes at deciduous sites was statistically similar at the $\alpha = 0.05$ level using Tukey's Studentized Range test. The mean

Table 6. Mean collection time for each forest type. The receivers were set to collect one position fix per second. Collection times longer than one position fix per second indicate signals from the satellites were interrupted.

Number of Position Fixes	Optimal time to collect total number of position fixes at 1 Position Fix per second (minutes)	Deciduous Sites (minutes)	Conifer Sites (minutes)	Open Sites (minutes)
60	1.00	1.95	3.11	1.09
100	1.67	2.50	3.18	1.84
200	3.33	4.75	6.22	3.58
300	5.00	6.84	8.44	5.49
500	8.33	11.34	14.23	8.82

collection time at deciduous sites for 200, 300, and 500 position fixes were all statistically different at the α = 0.05 level. Collection times at coniferous sites were statistically similar for 60 and 100 position fixes, similar for 200 and 300 position fixes, while 500 position fixes was distinct from the others. Each number of position fixes at open sites were significantly different from all the other position fixes. In other words, collection times at open sites for each number of position fixes were significantly longer than the previous number of position fixes and significantly shorter than the next higher number of position fixes.

Time to Lock:

The time the rover receiver took to first lock onto four satellites and compute a position was recorded as the time to lock. The mean time to lock for all canopy and terrain combinations was 1.49 minutes with the 90 percentile at 1.78 minutes and the 95 percentile at 2.5 minutes. The ANACOVA results show that there were no significant factors affecting the time to lock. As can be seen in Table 7, time to lock means ranged from 1.08 minutes at deciduous, ridge sites to 1.68 minutes at conifer, ridge sites. Tukey's Studentized Range test found no significant differences among the means at the α = 0.05 level.

Table 7. The mean time for the receiver to lock onto the signal of four satellites and compute a position.

Terrain	Deciduous Sites (minutes)	Conifer Sites (minutes)	Open Sites (minutes)
Ridge	1.08	1.68	1.48
Slope	1.60	1.66	1.36
Valley	1.53	1.59	1.43

Accuracy as a function of Distance from the Base-Station:

Six National Geodetic Survey markers were located along the Interstate-81 corridor between Blacksburg, Virginia and Shenandoah National Park (Figure 6). These points were visited nine times between May 1993 and April 1994. Five minutes of position data, approximately 300 position fixes, were acquired at each visit. The points for the distance study ranged from 43.6 km to 237.7 km from the Virginia Tech base-station. Detailed point information is located in Appendix. Mean accuracy ranged from 1.484 meters at the farthest site to 2.43 meters at the site 169 kilometers from the base-station (Figure 7).

Tukey's Studentized Range test found that there were no differences among the mean accuracies for each distance study site. The most accurate observation occurred at the point farthest from the base-station. PDOPs were not a major factor affecting accuracy. Although there is not a significant difference among the means there is the appearance of decreasing accuracy with distance from the base station. The majority of accuracies that occurred at each site were in the one to two meter range. For the site with the lowest accuracy there was one outlier of six meters that raised its mean above the others.

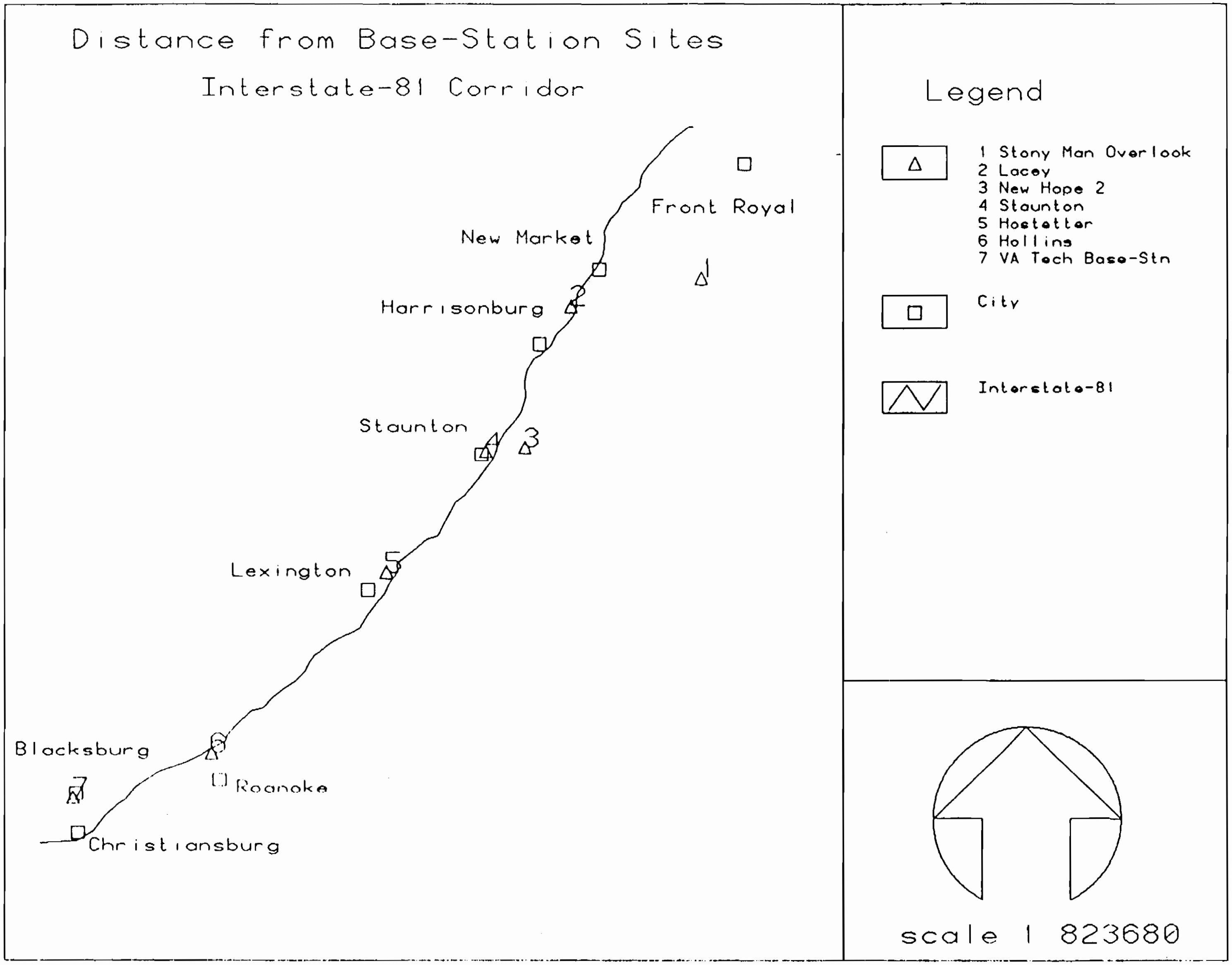

Figure 6. Position of points used for the distance studies. All points were first order National Geodetic Survey markers. Most points were located along the Interstate-81 corridor.

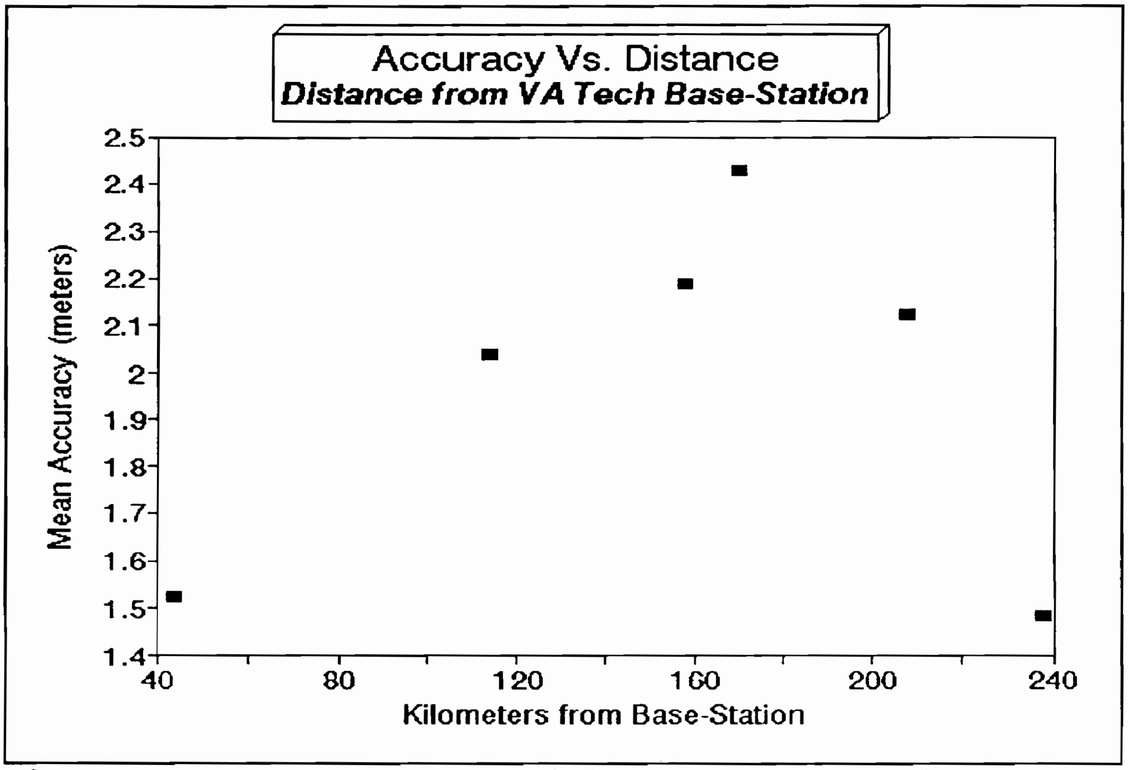

Figure 7. The accuracy of position measurements with respect to the distance of the point from the Virginia Tech base-station. Each point is the mean of nine samples of 300 position fixes. All positions were collected with PDOPs less than 4.2.

GPS to GIS conversion:

GPS data from the Big Meadows area in Shenandoah National Park were used to test for GIS data conversion. Position data were collected in the meadow in late January 1993. The day was rainy and foggy with visibility reduced to less than 100 meters. Position data were acquired by walking the receiver and antenna around the perimeter of the meadow. Position data for the entire meadow area were collected in one hour.

The position data were then converted to a .DXF format. The .DXF format is compatible with Atlas-GIS, one system used at SNP. The position data were then used to produce a map (Figure 8).

The SNP Meadow management plan produced a color infrared photo and a vegetation map of the meadow (Figures 9 and 10). The management plan stated that the size of the meadow was approximately 100 acres. Through GIS analysis of the GPS acquired data, the size of the meadow was computed to be 111 acres. The whole process of converting GPS data to GIS data was straight forward and simple using the import and export formats of each software package. Later tests of Trimble GPS data conversion for analysis in ARC/INFO were also accomplished without problems.

Issues of accuracy with GPS data are important to GIS users. National Map Accuracy Standards (NMAS) state that the

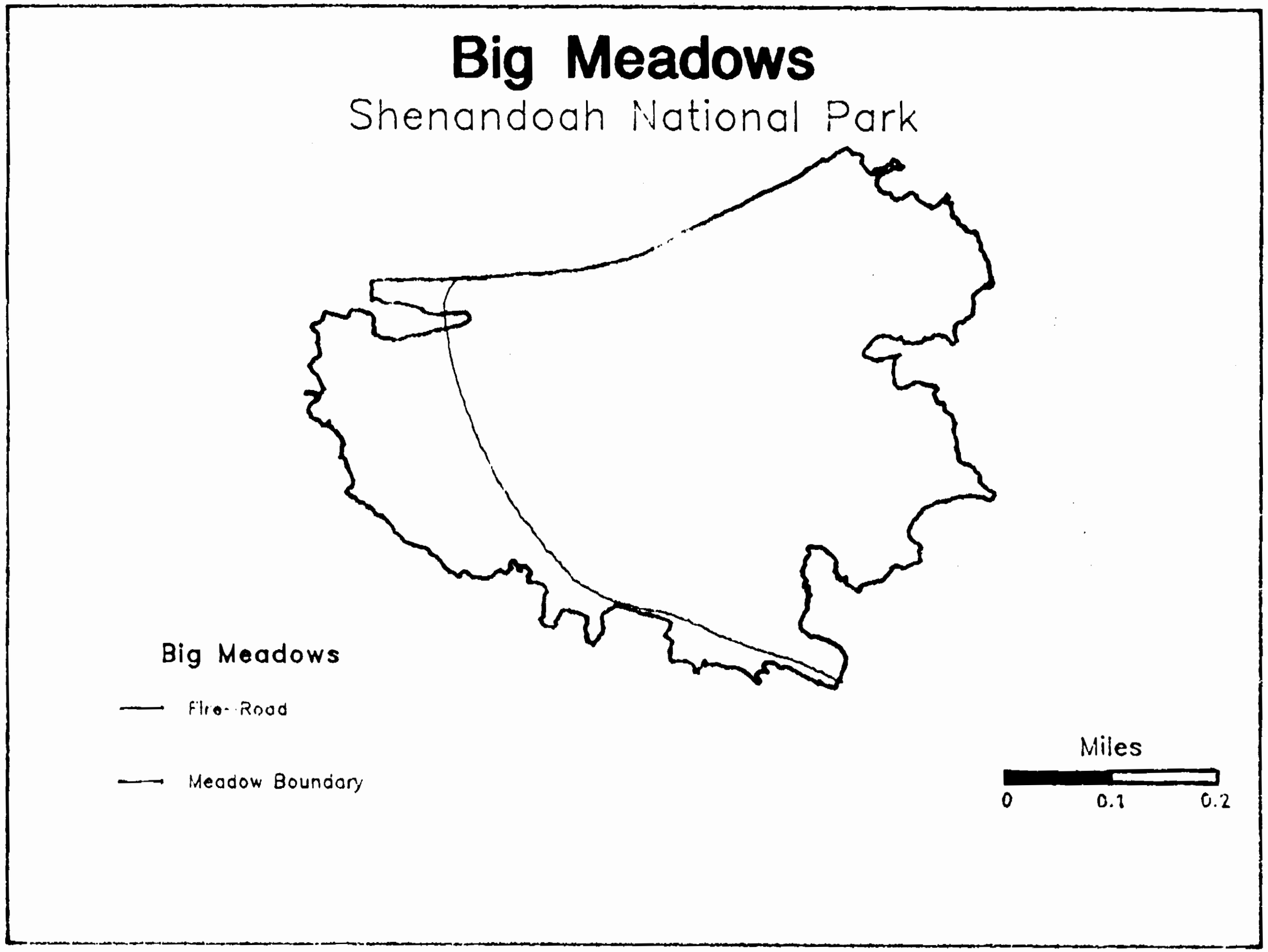

Figure 8. Map of Big Meadows produced with 1993 GPS collected data downloaded to Atlas-GIS.

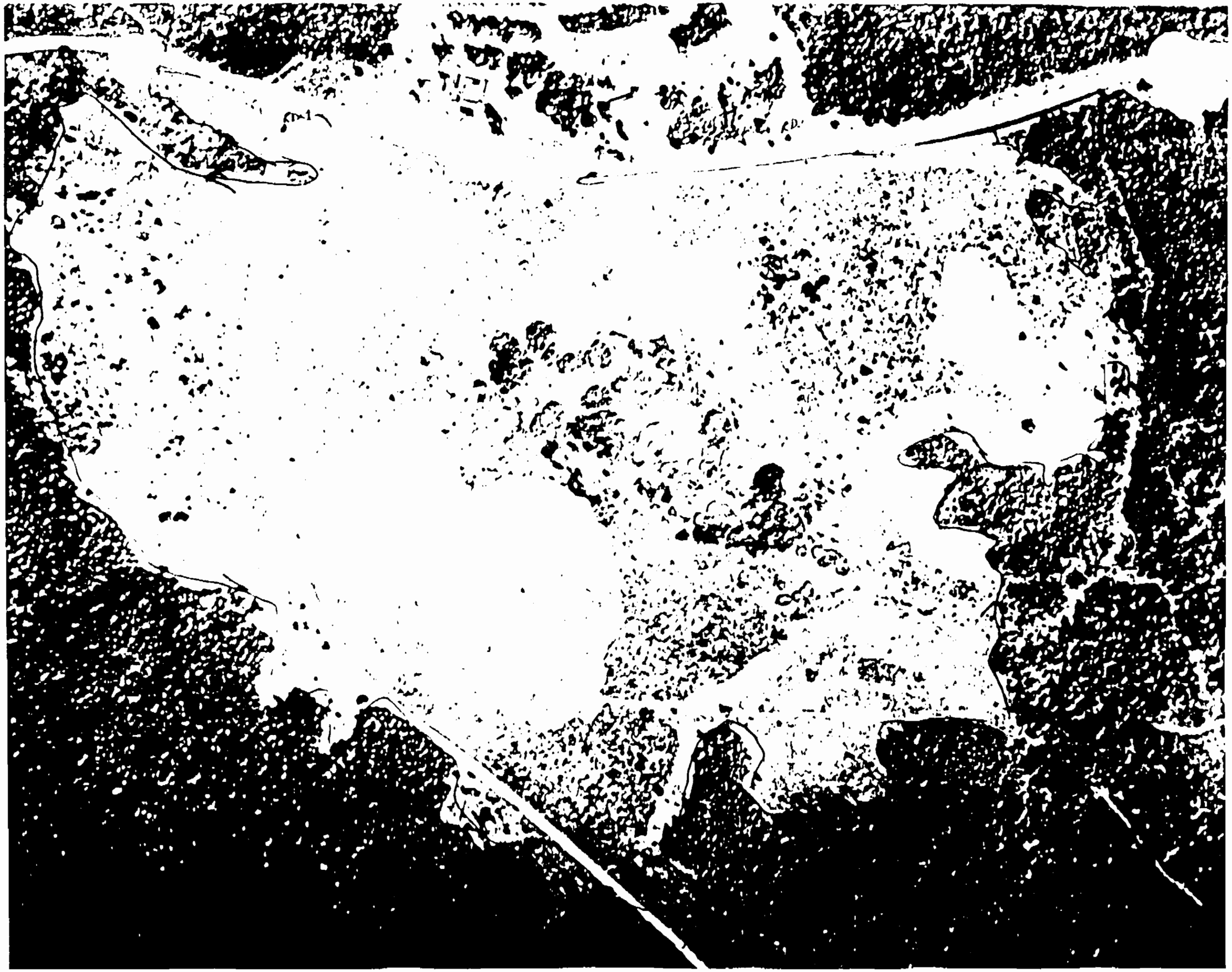

Figure 9. Color infrared photo of Big Meadows taken in 1985.

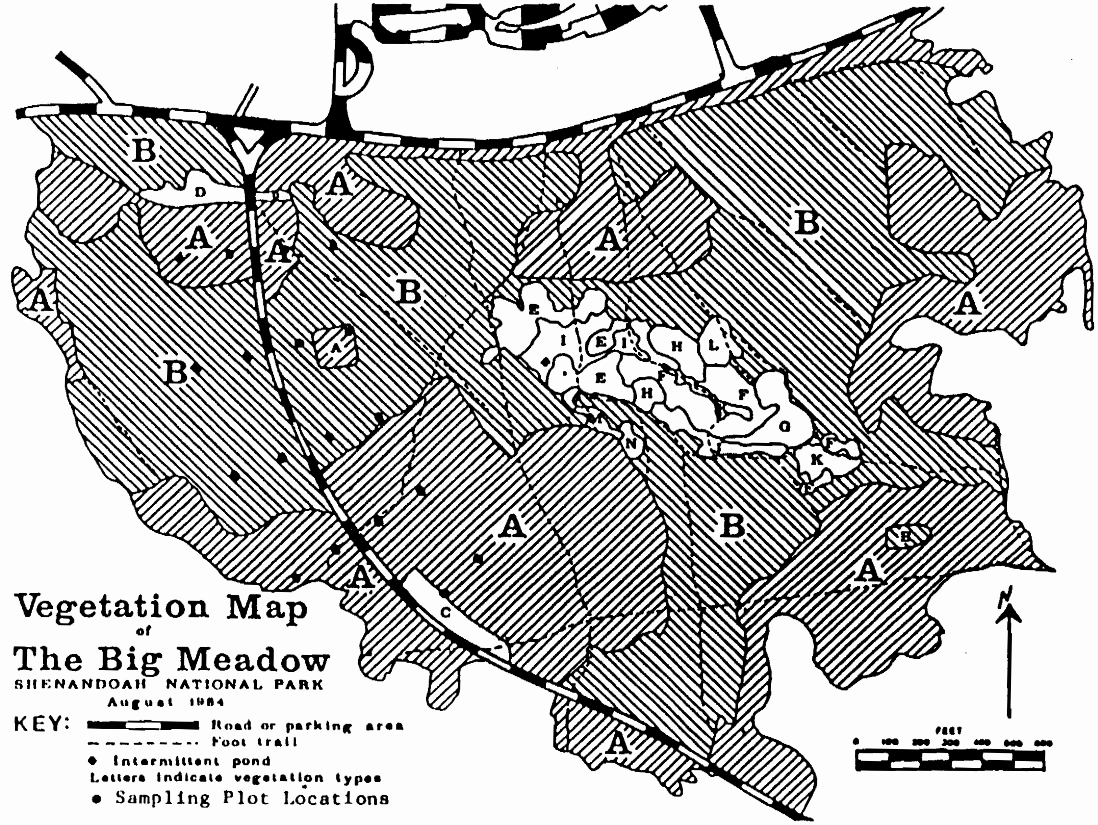

Figure 10. Vegetation Map of Big Meadows produced in 1984.

horizontal accuracy of maps "on publication scales larger than 1:20,000, not more than 10 percent of the points tested shall be in error by more than 1/30 inch, measured on the publication scale; for maps on publication scales of 1:20,000 or smaller, 1/50 inch (Thompson 1982)." For 1:24,000 maps, which is the scale of 7.5 minute quads frequently used by many agencies, 90 percent of the time the accuracy of a point should be within 12.19 meters of its actual position.

Of all the point data collected and differentially corrected, 95 percent of the point data was within 10.2 meters of the actual position. This is well within NMAS limits. Consideration must be taken, however, when stating the accuracy of lines produced by GPS. Each point along a line has a higher margin of error than do points at which large number of position fixes are collected and averaged. This problem may be solved by collecting large numbers of points at both ends of a straight line and connecting the resulting mean of each position. This becomes more difficult with highly irregular shapes.

CONCLUSIONS

The number of position fixes significantly affected positional accuracy of GPS determined positions in both autonomous and differential correction mode. Canopy significantly affects the positional accuracy of GPS determined positions only in differential correction mode.

Understanding the terrain and the canopy type before going into the field is important in the process of minimizing position error. Preplanning software helps predict satellite visibility, but the actual trunks, branches, and foliage further degrade accuracies and are not predictable on a per-point basis. Three to seven meter accuracies are possible under forested conditions, but require 200 or more consecutive position fixes and longer collection times than under clear sky conditions. Accuracies under forested canopies with differential correction are more likely to range from 3 m to 8 m when between 60 and 500 points are collected and averaged, depending on canopy type and terrain.

Canopy and terrain interference reduce accuracies and efficiencies because the optimal set of satellites may not be visible even though they are above the planar horizon. This forces data acquisitions with higher PDOPs, and thus causes slightly lower accuracies. The mean time required for initial satellite lock varies between one and two minutes. The major difference between the canopy types was the position collection times. Collection times were nearly twice as long under conifer canopies than at open sites. Collection times for deciduous sites were midway between those of open and coniferous sites.

Distances of 240 kilometers or less did not significantly affect positional accuracy. All position data collected within 240 km of the Virginia Tech base-station were differentially corrected and ranged in mean accuracy from 1.48 m to 2.43 m. The import of GPS data to GIS databases was accomplished without problem. This is encouraging knowing that much of the future sources of data for GISs will be from GPS data.

The significance of point data acquired by a GPS receiver can not be understated. However, much of the data collected by GPS receivers for input into a GIS are of line and polygon nature. Many boundaries are continuous and the line delineating the place where a meadow ends and a forest begins is not often obvious. It is important that protocol is developed in order to consistently record feature boundaries with GPS receivers.

Further research in the GPS accuracy field could include line and polygon accuracy. The accuracy of a single position along a line collected by a GPS receiver is less than that of a single point resulting from the mean of a number of position fixes. Lines collected by GPS receivers may require a buffer zone around the line to delineate the approximate accuracy of the line. A buffer of five meters on each side of a boundary for an area greatly sways the size of the area. The development and testing of different algorithms that increase the accuracy of a GPS collected lines or polygons by using splines, running averages, or filters would find rapid utilization in the GPS/GIS field.

References

August, Peter, J. Michaud, C. Labash, C. Smith. 1994. GPS for Environmental Applications: Accuracy and Precision of Locational Data. Photogrammetric Engineering & Remote Sensing, Vol 60, No 1, pp 41-45.

Bolstad, Paul V. 1993. GPS Basics: Forestry Applications. the Compiler. Fall. Vol. 11, No.3. pp 4-7.

Evans, David L., Ronald W. Carraway, George T. Simmons. 1992. Use of Global Positioning System (GPS) for forest plot location. South. J. Appl. For. 16(2). pp 67-70.

Gerlach, Frederick L., Anthony Jasumback. 1989. Global Positioning System canopy effects study. USDA For. Serv. Technology and Development Program MTDC 89-34. 18p.

Gilbert, Chuck. 1994. Purchasing Your Own Base-Station: A Look at Features and Benefits. Earth Observation Magazine. Vol 3. No 2. pp 44-48.

Hurn, Jeff. 1989. GPS: A guide to the next utility. Trimble Navigation Ltd. 76p.

Kruczynski, Leonard R., Anthony Jasumback. 1993. Forestry Management Applications: Forest Service experiences with GPS. Journal of Forestry. August. pp 20-24.

Liu, Calvin J. 1993. GPS Accuracy: Can GPS Fill the Need for GIS?. the Compiler. Fall. Vol. 11, No. 3. pp 18-27.

Milliken, R. J., Zoller, C. J. 1980. Principle of Operation of NAVSTAR and System Characteristics. Global Positioning System. Papers published in Navigation. Vol. 1.

National Park Service Geographic Information Sourcebook. 1993. Release No. 1. July. pp 5.1-5.1.11.

Slonecker Terrence., Brenda Groskinsky. 1993. GPS applications in the U.S. Environmental Protection Agency. Surveying and Land Information Systems. Vol. 53, No. 2. pp 117-124.

Thompson, M. M. 1982. Maps for America, 2nd ed. Washington D.C.: U.S. Geological Survey. p.104.

Wilkie, David S. 1989. Performance of a Backpack GPS in a Tropical Rain Forest. Photogrammetric Engineering and Remote Sensing. Vol 55, No. 12, pp 44-48.

Wells David. 1986. Guide to GPS Positioning. Canadian GPS Associates.

Wilson, R. L. 1990. Elementary Forest Surveying and Mapping II. O.S.U. Book Stores, Inc. Corvallis, Oregon. 287 pp.

APPENDIX

Detailed information on each point used in this study.

Detailed Point Information

1) The point name is either the official National Geodetic Survey marker name or the common name used for the point during this study.

2) The point number is the number assigned to the point when it was added to the study. The numbers beginning with 0 are in the Blacksburg vicinity. The numbers beginning with 1 are in Shenandoah National Park. Point numbers beginning with 2 were used exclusively for the distance study.

3) The coordinates are in Latitude and Longitude based on the North American Datum of 1983 (NAD-83).

4) The Survey origin is the point from which the site was surveyed.

5) The Carrier Phase Dilution of Precision (CPDOP) is a numerical representation of the approximate geometric quality for the carrier phase positioning (Magellan 1992). The values are as follows:

CPDOP	Geometric Quality
<=20	Excellent
20-44	Good
45-74	Fair
75-99	Poor
>=100	Unreliable

6) The error of closure is the distance in meters the end of a closed traverse is from the starting point.

7) The distance from the base-station refers to the distance in kilometers the study point is from the base-station.

8) The Forest Type is the dominant tree type around and over the study site. The forest types included deciduous sites, coniferous sites, and open areas.

9) Terrain refers to the characteristics of the land surrounding the study site. The terrain was either ridge-top, slope, or valley.

10) Canopy Closure was determined with a canopy densiometer and refers to the amount of sky blocked by the surrounding forest overstory.

11) Basal area (BA) is a representation of forest stand density. BA is the area in square feet at breast height of the tree stems per acre.

12) Gradient is the slope in degrees of the study site.

13) Aspect is the direction the study site faces in azimuth degrees.

14) Each site was assessed for obstructions from the terrain and canopy. The obstructions were recorded in degrees above the horizon for the bearings N, NE, E, SE, S, SW, W, and NW.

Deciduous Ridge-Top

Point Name:	Dickey's Ridge		Degrees above the horizon Terrain	Canopy
Point Number:	118	North	0	90
Coordinates:	38 51 20.088 N	North-East	0	90
NAD-83	78 12 20.887 W	East	0	90
Survey Origin:	NGS	South-East	0	90
CPDOP:	N/A	South	0	90
Error of Closure (m):	0.899	South-West	3	90
Distance from		West	3	90
Base-Station (km):	41.96	North-West	1	90
Forest Canopy:	Deciduous			
Terrain:	Ridge-Top			
Canopy Closure:	94%			
Basal Area (sq.ft./ac):	140			
Gradient (degrees):	2			
Aspect (Azimuth):	340			

Point Name:	Price's Mtn.		Degrees above the horizon Terrain	Canopy
Point Number:	010	North	0	90
Coordinates:	37 11 14.52 N	North-East	0	90
NAD-83	80 27 24.17 W	East	0	90
Survey Origin:	CP	South-East	4	90
CPDOP:	15.7	South	4	90
Error of Closure (m):	0.346	South-West	3	90
Distance from		West	2	90
Base-Station (km):	5.07	North-West	0	90
Forest Canopy:	Deciduous			
Terrain:	Ridge-Top			
Canopy Closure:	94%			
Basal Area (sq.ft./ac):	100			
Gradient (degrees):	3			
Aspect (Azimuth):	18			

Point Name:	Brush Ridge Hardwood		Degrees above the horizon Terrain	Canopy
Point Number:	121	North	0	90
Coordinates:	37 16 39.511 N	North-East	0	90
NAD-83	80 26 59.873 W	East	0	90
Survey Origin:	CP	South-East	0	90
CPDOP:	21.2	South	0	90
Error of Closure (m):	0.09	South-West	0	90
Distance from		West	0	90
Base-Station (km):	6.435	North-West	0	90
Forest Canopy:	Deciduous			
Terrain:	Ridge-Top			
Canopy Closure:	87%			
Basal Area (sq.ft./ac):	90			
Gradient (degrees):	2			
Aspect (Azimuth):	0			

Deciduous Slope

			Degrees above the horizon	
Point Name:	Hemlock Springs Slope Hardwood		Terrain	Canopy
Point Number:	121	North	0	90
Coordinates:	38 35 47.360 N	North-East	0	90
NAD-83	78 21 35.775 W	East	2	90
Survey Origin:	CP	South-East	13	90
CPDOP:	21.2	South	17	90
Error of Closure (m):	0.871	South-West	22	90
Distance from		West	24	90
Base-Station (km):	10.45	North-West	17	90
Forest Canopy:	Deciduous			
Terrain:	Slope			
Canopy Closure:	91%			
Basal Area (sq.ft./ac):	90			
Gradient:	24			
Aspect:	34			

			Degrees above the horizon	
Point Name:	Brush Slope Hardwood		Terrain	Canopy
Point Number:	012	North	11	90
Coordinates:	37 16 37.377 N	North-East	3	90
NAD-83	80 26 58.562 W	East	6	90
Survey Origin:	NGS	South-East	0	90
CPDOP:	n/a	South	0	90
Error of Closure (m):	0.28	South-West	0	90
Distance from		West	6	90
Base-Station (km):	6.36	North-West	14	90
Forest Canopy:	Deciduous			
Terrain:	Slope			
Canopy Closure:	98%			
Basal Area (sq.ft./ac):	80			
Gradient:	16			
Aspect:	154			

			Degrees above the horizon	
Point Name:	Hanse Slope Hardwood		Terrain	Canopy
Point Number:	120	North	6	90
Coordinates:	38 23 17.019 N	North-East	19	90
NAD-83	78 36 16.787 W	East	23	66
Survey Origin:	NGS	South-East	19	72
CPDOP:	n/a	South	13	90
Error of Closure (m):	0.64	South-West	2	90
Distance from		West	2	90
Base-Station (km):	21.07	North-West	2	90
Forest Canopy:	Deciduous			
Terrain:	Slope			
Canopy Closure:	87%			
Basal Area (sq.ft./ac):	90			
Gradient:	23			
Aspect:	270			

Deciduous Valley

			Degrees above the horizon	
Point Name:	Stanard offset		Terrain	Canopy
Point Number:	123	North	9	90
Coordinates:	38 17 52.676 N	North-East	5	90
NAD-83	78 26 44.674 W	East	3	90
Survey Origin:	NGS	South-East	0	90
CPDOP:	n/a	South	0	90
Error of Closure (m):	n/a	South-West	3	90
Distance from		West	8	90
Base-Station (km):	24.99	North-West	11	90
Forest Canopy:	Deciduous			
Terrain:	Valley			
Canopy Closure:	88%			
Basal Area (sq.ft./ac):	120			
Gradient:	9			
Aspect:	180			

			Degrees above the horizon	
Point Name:	Lower Caldwell Hardwood		Terrain	Canopy
Point Number:	015	North	10	90
Coordinates:	37 20 14.326 N	North-East	8	90
NAD-83	80 19 19.549 W	East	6	90
Survey Origin:	CP	South-East	14	90
CPDOP:	16	South	15	90
Error of Closure (m):	0.40	South-West	10	90
Distance from		West	6	90
Base-Station (km):	15.4	North-West	10	90
Forest Canopy:	Deciduous			
Terrain:	Valley			
Canopy Closure:	100%			
Basal Area (sq.ft./ac):	140			
Gradient:	0			
Aspect:	n/a			

			Degrees above the horizon	
Point Name:	Railroad Hardwood		Terrain	Canopy
Point Number:	016	North	12	90
Coordinates:	37 10 33.505 N	North-East	10	90
NAD-83	80 28 28.815 W	East	9	90
Survey Origin:	CP	South-East	25	90
CPDOP:	17.4	South	26	90
Error of Closure (m):	0.51	South-West	37	90
Distance from		West	11	90
Base-Station (km):	7.06	North-West	10	90
Forest Canopy:	Deciduous			
Terrain:	Valley			
Canopy Closure:	86%			
Basal Area (sq.ft./ac):	80			
Gradient:	0			
Aspect:	n/a			

Coniferous Ridge-Top

			Degrees above the horizon	
Point Name:	Mile 37 Ridge Conifer		Terrain	Canopy
Point Number:	119	North	0	90
Coordinates:	38 17 15.466 N	North-Eas	3	90
NAD-83	78 20 37.141 W	East	0	90
Survey Origin:	CP	South-Eas	0	90
CPDOP:	11.8	South	0	90
Error of Closure (m):	0.42	South-We	0	90
Distance from		West	0	90
Base-Station (km):	13.47	North-We	0	90
Forest Canopy:	Coniferous			
Terrain:	Ridge-Top			
Canopy Closure:	70%			
Basal Area (sq.ft./ac):	180			
Gradient:	0			
Aspect:	n/a			

			Degrees above the horizon	
Point Name:	Big Meadows Ridge Conifer		Terrain	Canopy
Point Number:	125	North	0	90
Coordinates:	38 30 51.497 N	North-Eas	0	90
NAD-83	78 26 30.845 W	East	0	90
Survey Origin:	CP	South-Eas	0	90
CPDOP:	15.9	South	0	90
Error of Closure (m):	0.90	South-We	0	90
Distance from		West	0	90
Base-Station (km):	1.14	North-We	0	90
Forest Canopy:	Coniferous			
Terrain:	Ridge-Top			
Canopy Closure:	88%			
Basal Area (sq.ft./ac):	90			
Gradient:	0			
Aspect:	n/a			

			Degrees above the horizon	
Point Name:	Brush Ridge Conifer		Terrain	Canopy
Point Number:	021	North	2	90
Coordinates:	37 16 27.185 N	North-Eas	2	90
NAD-83	80.27 18.724 W	East	2	90
Survey Origin:	CP	South-Eas	4	90
CPDOP:	34.9	South	2	90
Error of Closure (m):	n/a	South-We	6	90
Distance from		West	2	90
Base-Station (km):	6.285	North-We	2	90
Forest Canopy:	Coniferous			
Terrain:	Ridge-Top			
Canopy Closure:	82%			
Basal Area (sq.ft./ac):	90			
Gradient:	3			
Aspect:	269			

Coniferous Slope

			Degrees above the horizon	
Point Name:	Hemlock Springs Slope Conifer		Terrain	Canopy
Point Number:	122	North	1	90
Coordinates:	38 35 46.832 N	North-Eas	1	90
NAD-83	78 21 36.741 W	East	15	90
Survey Origin:	CP	South-Eas	23	90
CPDOP:	21.2	South	27	90
Error of Closure (m):	0.853	South-We	24	90
Distance from		West	22	90
Base-Station (km):	10.42	North-We	10	90
Forest Canopy:	Coniferous			
Terrain:	Slope			
Canopy Closure:	97%			
Basal Area (sq.ft./ac):	210			
Gradient:	26			
Aspect:	328			

			Degrees above the horizon	
Point Name:	Upper Cauldwell Slope Conifer		Terrain	Canopy
Point Number:	013	North	11	90
Coordinates:	37 20 21.128 N	North-Eas	6	90
NAD-83	80 19 30.730 W	East	3	90
Survey Origin:	CP	South-Eas	7	90
CPDOP:	45.8	South	7	90
Error of Closure (m):	0.328	South-We	6	90
Distance from		West	5	90
Base-Station (km):	15.41	North-We	14	90
Forest Canopy:	Coniferous			
Terrain:	Slope			
Canopy Closure:	94%			
Basal Area (sq.ft./ac):	110			
Gradient:	14			
Aspect:	164			

			Degrees above the horizon	
Point Name:	Rail Road Slope Conifer		Terrain	Canopy
Point Number:	014	North	9	90
Coordinates:	37 10 28.684 N	North-Eas	10	90
NAD-83	80 28 16.844 W	East	9	90
Survey Origin:	CP	South-Eas	12	90
CPDOP:	26.5	South	19	90
Error of Closure (m):	0.853	South-We	29	90
Distance from		West	27	90
Base-Station (km):	6.986	North-We	16	90
Forest Canopy:	Coniferous			
Terrain:	Slope			
Canopy Closure:	91%			
Basal Area (sq.ft./ac):	100			
Gradient:	31			
Aspect:	44			

Coniferous Valley

			Degrees above the horizon	
Point Name:	Headquarters Valley Conifer		Terrain	Canopy
Point Number:	124	North	9	90
Coordinates:	38 39 59.074 N	North-East	11	90
NAD-83	78 22 15.498 W	East	12	90
Survey Origin:	CP	South-East	14	90
CPDOP:	15.1	South	12	90
Error of Closure (m):	0.743	South-West	8	90
Distance from		West	10	90
Base-Station (km):	16.87	North-West	12	90
Forest Canopy:	Coniferous			
Terrain:	Valley			
Canopy Closure:	98%			
Basal Area (sq.ft./ac):	80			
Gradient:	0			
Aspect:	n/a			

			Degrees above the horizon	
Point Name:	Rail Road Valley Conifer		Terrain	Canopy
Point Number:	017	North	19	90
Coordinates:	37 10 31.407 N	North-East	12	90
NAD-83	80 28 14.399 W	East	20	90
Survey Origin:	CP	South-East	11	90
CPDOP:	26.5	South	12	90
Error of Closure (m):	0.853	South-West	14	90
Distance from		West	7	90
Base-Station (km):	6.88	North-West	15	90
Forest Canopy:	Coniferous			
Terrain:	Valley			
Canopy Closure:	99%			
Basal Area (sq.ft./ac):	100			
Gradient:	6			
Aspect:	180			

			Degrees above the horizon	
Point Name:	Caldwell Road Valley Conifer		Terrain	Canopy
Point Number:	024	North	22	90
Coordinates:	37 18 56.766 N	North-East	20	90
NAD-83	80 24 02.663 W	East	10	90
Survey Origin:	CP	South-East	12	90
CPDOP:	20.8	South	13	90
Error of Closure (m):	0.314	South-West	10	90
Distance from		West	11	90
Base-Station (km):	10.36	North-West	22	90
Forest Canopy:	Coniferous			
Terrain:	Valley			
Canopy Closure:	96%			
Basal Area (sq.ft./ac):	240			
Gradient:	0			
Aspect:	n/a			

Open Ridge-Top

			Degrees above the horizon	
Point Name:	Stony Man Overlook		Terrain	Canopy
Point Number:	105	North	0	0
Coordinates:	38 36 42.083 N	North-East	5	0
NAD-83	78 21 46.041 W	East	1	11
Survey Origin:	NGS	South-East	1	11
CPDOP:	n/a	South	5	6
Error of Closure (m):	n/a	South-West	5	6
Distance from		West	0	0
Base-Station (km):	11.67	North-West	0	0
Forest Canopy:	Open			
Terrain:	Ridge-Top			
Canopy Closure:	n/a			
Basal Area (sq.ft./ac):	n/a			
Gradient:	n/a			
Aspect:	n/a			

			Degrees above the horizon	
Point Name:	Fork Mtn. Azimuth Marker		Terrain	Canopy
Point Number:	107	North	0	0
Coordinates:	38 30 47.011 N	North-East	0	0
NAD-83	80 25 17.981 W	East	0	0
Survey Origin:	NGS	South-East	0	3
CPDOP:	n/a	South	0	5
Error of Closure (m):	n/a	South-West	5	9
Distance from		West	7	11
Base-Station (km):	1.144	North-West	5	0
Forest Canopy:	Open			
Terrain:	Ridge-Top			
Canopy Closure:	5%			
Basal Area (sq.ft./ac):	n/a			
Gradient:	7			
Aspect:	27			

			Degrees above the horizon	
Point Name:	Blacks-Golf Ridge Open		Terrain	Canopy
Point Number:	001	North	0	0
Coordinates:	38 13 29.562 N	North-East	0	0
NAD-83	80 23 43.229 W	East	0	0
Survey Origin:	NGS	South-East	0	0
CPDOP:	n/a	South	0	0
Error of Closure (m):	n/a	South-West	0	0
Distance from		West	0	0
Base-Station (km):	2.41	North-West	0	0
Forest Canopy:	Open			
Terrain:	Ridge-top			
Canopy Closure:	n/a			
Basal Area (sq.ft./ac):	n/a			
Gradient:	n/a			
Aspect:	n/a			

Open Slope

Point Name:	Hemlock Springs Carrier Phase		Degrees above the horizon Terrain	Canopy
Point Number:	126	North	0	18
Coordinates:	38 35 46.917 N	North-East	0	14
NAD-83	78 21 38.876 W	East	3	10
Survey Origin:	CP	South-East	14	22
CPDOP:	21.2	South	18	39
Error of Closure (m):	n/a	South-West	14	24
Distance from		West	14	14
Base-Station (km):	10.39	North-West	2	19
Forest Canopy:	n/a			
Terrain:	Slope			
Canopy Closure:	n/a			
Basal Area (sq.ft./ac):	n/a			
Gradient:	20			
Aspect:	344			

Point Name:	Upper Caldwell Carrier Phase		Degrees above the horizon Terrain	Canopy
Point Number:	021	North	15	42
Coordinates:	37 20 20.071 N	North-East	6	22
NAD-83	80 19 31.228 W	East	7	7
Survey Origin:	CP	South-East	6	6
CPDOP:	45.8	South	9	9
Error of Closure (m):	n/a	South-West	6	6
Distance from		West	9	9
Base-Station (km):	6.285	North-West	14	37
Forest Canopy:	Open			
Terrain:	Slope			
Canopy Closure:	n/a			
Basal Area (sq.ft./ac):	n/a			
Gradient:	13			
Aspect:	150			

Point Name:	Blacksburg Slope		Degrees above the horizon Terrain	Canopy
Point Number:	023	North	8	0
Coordinates:	37 13 13.731 N	North-East	2	0
NAD-83	80 23 17.577 W	East	3	0
Survey Origin:	CP	South-East	0	0
CPDOP:	18.2	South	3	0
Error of Closure (m):	n/a	South-West	14	0
Distance from		West	14	0
Base-Station (km):	3.065	North-West	15	0
Forest Canopy:	Open			
Terrain:	Slope			
Canopy Closure:	n/a			
Basal Area (sq.ft./ac):	n/a			
Gradient:	14			
Aspect:	220			

Open Valley

			Degrees above the horizon	
Point Name:	Lower Caldwell Carrier Phase		Terrain	Canopy
Point Number:	018	North	11	11
Coordinates:	37 20 12.999 N	North-East	9	9
NAD-83	80 19 20.997 W	East	9	37
Survey Origin:	CP	South-East	15	24
CPDOP:	16	South	9	9
Error of Closure (m):	n/a	South-West	6	9
Distance from		West	6	6
Base-Station (km):	15.35	North-West	11	11
Forest Canopy:	Open			
Terrain:	Valley			
Canopy Closure:	n/a			
Basal Area (sq.ft./ac):	n/a			
Gradient:	n/a			
Aspect:	n/a			

			Degrees above the horizon	
Point Name:	Caldwell Road Carrier Phase		Terrain	Canopy
Point Number:	022	North	16	32
Coordinates:	37 18 53.252 N	North-East	13	13
NAD-83	80 24 10.027 W	East	7	20
Survey Origin:	CP	South-East	12	28
CPDOP:	20.8	South	13	20
Error of Closure (m):	n/a	South-West	8	15
Distance from		West	10	10
Base-Station (km):	10.23	North-West	18	30
Forest Canopy:	Open			
Terrain:	Valley			
Canopy Closure:	n/a			
Basal Area (sq.ft./ac):	n/a			
Gradient:	n/a			
Aspect:	n/a			

			Degrees above the horizon	
Point Name:	Rail Road Valley Carrier Phase		Terrain	Canopy
Point Number:	020	North	17	19
Coordinates:	37 10 32.158 N	North-East	17	28
NAD-83	80 28 25.558 W	East	11	14
Survey Origin:	CP	South-East	3	3
CPDOP:	17.4	South	14	17
Error of Closure (m):	n/a	South-West	19	19
Distance from		West	6	8
Base-Station (km):	7.04	North-West	15	29
Forest Canopy:	Open			
Terrain:	Valley			
Canopy Closure:	n/a			
Basal Area (sq.ft./ac):	n/a			
Gradient:	2			
Aspect:	188			

Distance Points

			Degrees above the horizon	
			Terrain	Canopy
Point Name:	Hollins			
Point Number:	205	North		
Coordinates:	37 21 10.179 N	North-East		
NAD-83	79 57 27.560 W	East		
Survey Origin:	NGS	South-East		
CPDOP:	n/a	South		
Error of Closure (m):	n/a	South-West		
Distance from		West		
Base-Station (km):	43.606	North-West		
Forest Canopy:	Open			
Terrain:	Distance Point			
Canopy Closure:	n/a			
Basal Area (sq.ft./ac):	n/a			
Gradient:	n/a			
Aspect:	n/a			

			Degrees above the horizon	
			Terrain	Canopy
Point Name:	Hostetter			
Point Number:	204	North		
Coordinates:	37 49 53.062 N	North-East		
NAD-83	79 22 58.938 W	East		
Survey Origin:	NGS	South-East		
CPDOP:	n/a	South		
Error of Closure (m):	n/a	South-West		
Distance from		West		
Base-Station (km):	113.94	North-West		
Forest Canopy:	Open			
Terrain:	Distance Point			
Canopy Closure:	n/a			
Basal Area (sq.ft./ac):	n/a			
Gradient:	n/a			
Aspect:	n/a			

			Degrees above the horizon	
			Terrain	Canopy
Point Name:	Staunton			
Point Number:	203	North		
Coordinates:	38 09 11.584 N	North-East		
NAD-83	79 04 08.584 W	East		
Survey Origin:	NGS	South-East		
CPDOP:	n/a	South		
Error of Closure (m):	n/a	South-West		
Distance from		West		
Base-Station (km):	157.741	North-West		
Forest Canopy:	Open			
Terrain:	Distance Point			
Canopy Closure:	n/a			
Basal Area (sq.ft./ac):	n/a			
Gradient:	n/a			
Aspect:	n/a			

Distance Points

			Degrees above the horizon	
			Terrain	Canopy
Point Name:	New Hope 2			
Point Number:	201	North		
Coordinates:	38 10 44.947 N	North-East		
NAD-83	78 55 01.170 W	East		
Survey Origin:	NGS	South-East		
CPDOP:	n/a	South		
Error of Closure (m):	n/a	South-West		
Distance from		West		
Base-Station (km):	169.876	North-West		
Forest Canopy:	Open			
Terrain:	n/a			
Canopy Closure:	n/a			
Basal Area (sq.ft./ac):	n/a			
Gradient:	n/a			
Aspect:	n/a			

			Degrees above the horizon	
			Terrain	Canopy
Point Name:	Lacey			
Point Number:	200	North		
Coordinates:	38 32 58.237 N	North-East		
NAD-83	78 45 40.895 W	East		
Survey Origin:	NGS	South-East		
CPDOP:	n/a	South		
Error of Closure (m):	n/a	South-West		
Distance from		West		
Base-Station (km):	207.337	North-West		
Forest Canopy:	Open			
Terrain:	n/a			
Canopy Closure:	n/a			
Basal Area (sq.ft./ac):	n/a			
Gradient:	n/a			
Aspect:	n/a			

			Degrees above the horizon	
			Terrain	Canopy
Point Name:	Stony Man Overlook			
Point Number:	105	North	0	0
Coordinates:	38 36 42.083 N	North-East	5	0
NAD-83	78 21 46.041 W	East	1	11
Survey Origin:	NGS	South-East	1	11
CPDOP:	n/a	South	5	6
Error of Closure (m):	n/a	South-West	5	6
Distance from		West	0	0
Base-Station (km):	237.721	North-West	0	0
Forest Canopy:	Open			
Terrain:	Ridge-Top			
Canopy Closure:	n/a			
Basal Area (sq.ft./ac):	n/a			
Gradient:	n/a			
Aspect:	n/a			

Vita

Christopher J. Deckert was born on August 17, 1970 in Waynesboro, Virginia. He attended Virginia Polytechnic Institute and State University, graduating in May of 1992 with a Bachelor of Science in Biology. In May of 1992 he continued his education at V.P.I. & S.U. where he earned his Master of Science in Forest Biometrics in May of 1994. Upon graduation he accepted employment with the Jesus Film Project in San Clemente, California.

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