# Forest Canopy, Terrain, and Distance Effects on Global Positioning System Point Accuracy

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## Abstract

*Tests were conducted to determine the realizable accuracies of the Global Positioning System under eastern North American forest 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 all combinations of three canopy (deciduous, conifer, open) and three terrain (ridge, slope, valley) types. Each site was visited over a span of nine months to collect position data, for ten replications per each of 27 sites to collect 60, 100, 200, 300, and 500 position fixes.*

*The mean differentially corrected positional accuracy for all sites was 4.35 metres, with 95 percent of the mean positions estimated within 10.2 metres of the true value. The least accurate differential position data were observed at conifer sites. Positional accuracy was higher for deciduous sites and highest at open sites. Mean positional accuracy increased from valley to ridge locations.*

*Mean accuracy increased with increasing number of position fixes collected per point. When the number of position fixes increased from 60 to 500, mean accuracy increased from 5.9 to 3.1 m under deciduous canopies, from 6.6 to 4.4 m under conifer canopies, and from 3.9 to 2.2 m under open skies.*

*The average time required by the GPS receiver to lock onto four satellites and begin collecting positions varied from one to two minutes, and collection times increased from open, through deciduous, to conifer sites.*

*There was an observed, but statistically non-significant, trend between accuracy and the field receiver's distance from the base station. Nine replicates of 300 position fixes were averaged for six sites, which ranged from 43 kilometres to 247 kilometres from a base station. Mean accuracy ranged from 1.48 metres to 2.43 metres.*

## 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. For example, the USDA Forest Service, National Park Service, EPA, and private forest management organizations have cited over 130 applications of GPS, including GIS database development; locating and mapping timber cruise plots, roads, and trails; fire control; law enforcement; and inventory of other biological resources (Kruczynski and Jasumback, 1993; NPS, 1993; Slonecker and Groskinsky, 1993).

Unfortunately, most previous GPS evaluations have been performed under "clear sky" conditions, where views to satellites are unobstructed by vegetation or terrain (August *et al.*, 1994), and most sub-canopy work has been conducted in the western United States (Kruczynski and Jasumback, 1993). 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. With increased use of GPS in forest resource settings, there is a need to understand the accuracies achievable in forested landscapes.

GPS positional accuracy depends on many factors (Milliken, 1980; Hurn, 1989; Bolstad, 1993; Liu, 1993). Selective Availability (SA) degrades the accuracy of the positions by deliberately introducing errors into the satellite navigational data and clock. Additional errors in the satellite clock, satellite ephemeris, receiver clock, and atmospheric delays further degrade accuracy. Satellite geometry also affects accuracy, and position dilution of precision (PDOP) is a numerical representation of the geometry of the satellite constellation. The lower the PDOP, the higher the expected positional accuracy (Wells, 1986).

Position data may be categorized as either autonomous (or uncorrected), or as differential (corrected). Autonomous positioning involves the use of one GPS receiver, and these data typically include errors from the satellite and receiver clock, the atmosphere and ionosphere, receiver noise, and SA. Autonomous positioning usually results in horizontal position accuracies of 10s to 100s of metres. Differential positioning utilizes two GPS receivers; one (base) receiver stationed over a known point and another (rover) receiver over unknown points. The two receivers collect data simultaneously, from the same or similar sets of satellites. This usually removes a portion of the errors due to system delays, atmosphere, and SA, which are similar for both base and roving receivers, although this relationship is expected to degrade with increasing base-to-rover distance (Gilbert, 1994). The base-station data and reference position are used to calculate a correction vector, which is then applied to rover data. Differential correction using the mean of 100 to 300 consecutive position fixes collected under unobstructed skies typically yields accuracies in the 2.1- to 3.4-metre range (August *et al.*, 1994).

The previous studies of sub-canopy GPS use have documented accuracies under some forest conditions. Gerlach (1989) focused on the effects of lodgepole pine (*Pinus contorta* Dougl.) trunks, branches, and foliage on positional accuracy. He found that the loss of the radio signal from the satellite was caused 23 percent of the time by the trunks, 28 percent by branches, and 36 percent by the foliage. Autono-

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mous position collection under the lodgepole pine canopy yielded an average difference between the actual position and the GPS-acquired position of 6.5 metres (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 *et al.* (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 6.6 m during navigation.

Tests of GPS efficiencies in the dense rain forests of northeastern Zaire, Africa resulted in quite long times to the first three-dimensional position fix. Position determination was obtained within 20 minutes in areas where elevation angles were less than 50 degrees, canopy closure was less than 20 percent, and there was a forest opening of > 0.125 ha (Wilkie, 1989). The high accuracy of the autonomous positions in these two studies was probably due to inactive SA. Today SA is constantly active and severely affects autonomous positional accuracy. However, these studies were also performed before completion of the satellite constellation, which may have led to higher PDOPs and thus lower accuracies.

## Objectives

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

- Determine the effect of satellite geometry, forest canopy, and terrain interference on realizable accuracies for differentially corrected data;
- Establish collection times using C/A code receivers; and
- Evaluate the effect of distance from the base station on the accuracy of differentially corrected position data.

## Methods

The effects of canopy type and terrain on horizontal positional accuracies were determined through point location measurements over a range of canopy, terrain, and satellite geometry conditions. Herein, canopy refers to tree overstory above each data collection site. Three terrain types (ridgetop, slope, and valley) and three canopy types (open, deciduous, and conifer) were represented. Each combination was replicated three times for a total of 27 sites. Most sites were clustered in two 120-km$^2$ areas of southwestern and western Virginia, centered on Blacksburg and Shenandoah National Park (SNP), respectively.

Accuracy (and error) in this study refers to the horizontal distance from GPS acquired positions to the "true" reference positions. Accuracies were determined from GPS measurements over precisely surveyed points. Reference coordinates for forested sites were determined by one of two methods. In the first method first- and second-order National Geodetic Survey (NGS) markers were located in the study areas. Points with desired canopy and terrain characteristics were located by means of traverses performed with standard surveying methods and an optical transit (Wilson, 1990). Traverses had an average error of closure of 0.58 m and a maximum error of closure of 0.89 m.

Because most recovered NGS markers were on ridgetops, carrier-phase GPS was used to establish points on slopes and in valleys. Our tests (with the Magellan 5000 Pro sub-meter kit) using paired first-order NGS markers resulted in an average horizontal error under 20 centimetres. Carrier phase positions were established in clear areas adjacent to desired forested sites, and sub-canopy points were established by means of traverses. A total of five forested sites were surveyed from NGS points, thirteen forested sites were surveyed from carrier phase points, three open sites were established directly on NGS points, and six open sites were established using carrier phase surveys.

Oaks (*Quercus* spp.) were the dominant tree species at the deciduous sites. Conifer sites were usually single-species stands of eastern hemlock (*Tsuga canadensis* (L.) Carr.), eastern red cedar (*Juniperus virginiana* L.), or Virginia pine (*Pinus virginiana* Mill.). The basal area for deciduous sites ranged from 18 m$^2$/ha to 32 m$^2$/ha and averaged 23 m$^2$/ha. The basal area at conifer sites ranged from 18 m$^2$/ha to 55 m$^2$/ha and averaged 31 m$^2$/ha. Measurement with a canopy densiometer indicated that the deciduous and conifer sites both averaged over 90 percent canopy closure. The average tree height was 20 metres and the forests surrounding all the sites were at least 50 years old. The conifer and deciduous sites in this study represent typical conditions for GPS data collection in naturally occurring eastern U.S. forests.

Horizon angles surrounding each site were determined with a clinometer. Horizons averaged 2 degrees above the horizontal 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. Horizons on slope sites ranged between 14 and 31 degrees upslope and a few degrees above the horizon downslope. 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, while data collected in SNP utilized a Trimble Pathfinder Professional for the base station. Both base stations were six-channel receivers. The coordinates for the SNP base station were determined by a third-order survey over a short (< 1-km) baseline. The antenna was located atop an 11-m tower for a clear view of the sky. The field- and base-station receivers were both set with an elevation mask of 15 degrees above the planar horizon and a one-second logging rate. All data collected were recorded using the manual three-dimensional mode. Receivers were set to record coordinates based on the WGS-84 geodetic datum and HAE, with appropriate conversion to NAD83 UTM zone 17-metre coordinates for comparison with reference data. Ten visits (replicates) were made to each site over a span of eight months to ensure a wide range of conditions and PDOPs. At each visit separate observations of 60, 100, 200, 300, and 500 fixes were logged. Collection of the deciduous forested data spanned May 1993 through September 1993. Analysis of receiver data was performed with PFINDER 2.10 software. 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. Mean positions were determined for each number of fixes for each site visit, along with the bias (average accuracy), variation, and statistical distribution of autonomous and differentially corrected positions. A range of PDOPs was collected at each site. In addition, average time to first position fix and speed for each subsequent position fix were recorded and summarized. When data collection took more than a few minutes, PDOP often changed, up to 15 times for a 500 position fix collection. Each PDOP that occurred during the session was recorded, and the average PDOP was calculated. Analyses of variance (ANOVA) and covariance (ANCOVA) were applied to the data. In the ANOVAs, accuracy was the dependent variable and categorical independent variables were canopy type (conifer/hardwood/open) and terrain (valley/slope/ridgetop). Independent variables were coded as dummy variables, with only main effects (no interactions), and parameters were estimated using a general linear models procedure. Significance for each variable was the mean square associated with an equal mean contrast, and dividing it by the estimated mean square error, and significance re-

Table 1. 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<br>90th Percentile<br>95th Percentile | Forest Type | | |
|---|---|---|---|
| Number of Position Fixes | Accuracy at Deciduous Sites (metres) | Accuracy at Conifer Sites (metres) | Accuracy at Open Sites (metres) |
| 60 | 5.9 | 6.6 | 3.9 |
| | 10.8 | 12.1 | 6.7 |
| | 15.5 | 14.5 | 7.8 |
| 100 | 4.9 | 6.5 | 3.5 |
| | 9.9 | 11.8 | 6.6 |
| | 11.0 | 14.1 | 7.5 |
| 200 | 4.2 | 5.8 | 2.9 |
| | 7.3 | 10.3 | 5.9 |
| | 8.7 | 14.0 | 6.3 |
| 300 | 3.8 | 5.2 | 2.4 |
| | 6.2 | 8.3 | 4.6 |
| | 7.7 | 10.3 | 5.3 |
| 500 | 3.1 | 4.4 | 2.2 |
| | 5.5 | 8.5 | 3.9 |
| | 6.3 | 10.6 | 4.5 |

ported from an appropriate F-table. $R^2$ for the model was computed as the ratio of the sum of squares for the model divided by sum of squares of the corrected total. $R^2$ reported for each variable are partials associated with the sum of squares attributable to the variable, divided by the total sum of squares. Similar methods were used in the ANCOVA, with the exception that PDOP was included as a continuous covariate.

As a test to observe distance effects on accuracy, six NGS points were located at distances between 43 and 237 kilometres from the Blacksburg 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 three-dimensional position fixes (approximately 300 position fixes). Accuracy as a function of distance was then evaluated.

## Results and Discussion

Positional accuracy varied by forest type and number of fixes (Table 1). Differentially corrected accuracies averaged a 4.3-m error over all forest types, terrain types, and number of position fixes. Ninety-five percent of the averaged differential position data were in error by less than 10.2 m, and 90 percent by less than 8.0 m. Only six mean observations (60 position fixes each) were greater than 20 metres after differential correction. There were three outliers between 30 and 40 metres. These may be due to multipath effects, which can cause reductions in accuracy.

Increasing the number of position fixes collected at a site greatly improved accuracy (Table 1). Mean positional accuracy increased from 5.9 m for 60 position fixes to 3.1 m for 500 position fixes under deciduous canopies. Mean accuracy under conifers increased the least of the three canopy types: from 6.6 m for 60 position fixes to 4.4 m for 500 position fixes. Open site accuracy increased from 3.9 m at 60 position fixes to 2.2 m for 500 position fixes.

Tukey's Studentized Range Test was applied to data collected under each canopy type to determine significance of differences in mean accuracy due to differences in the number of position fixes ($\alpha = 0.05$, Table 1). 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 under all types. This indicates the substantial variation in accuracies within each number of fixes is statistically large when compared to differences among different numbers of fixes.

The ANOVA 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 increase in PDOPs as terrain changed from ridge down across slopes and into valleys.

ANOVA significance and $R^2$s indicate that terrain was least important and canopy type most important in determining positional accuracy (Table 2). Tukey's Studentized range test on open sites found mean positional accuracy on ridges were significantly better than those on slope and valley sites. The slope and valley sites were statistically similar. Terrain was not a significant factor at deciduous sites. Mean accuracies for ridge and valley sites in conifer forests were statistically different, while slope sites were intermediate and statistically indistinguishable from both ridge and valley sites. At conifer sites, there was a gradual decrease in accuracy from ridgetops to valleys (Figure 1).

Data in this study were collected primarily to estimate accuracies for point feature coordinates determined through averaging a number of fixes. However, they also give an indication of expected accuracies when field-digitizing linear features. Typically, linear features are digitized by traveling more or less continuously along the feature with the GPS receiver, collecting positions at a constant frequency. Thus, each vertex is represented by a single point. These points will be expected to vary from the true boundary, with the average distance or distribution determined by the distribution of single position fixes about the mean. Because distance errors are usually measured at right angles to the lines represented, the errors will be less than those observed around a single point. With a spherical distribution, this error reduction is approximately 0.6366, on average (Burrough, 1986). Thus, the observed spherical distribution of accuracies about a point may be combined with this average factor to estimate average error for a straight linear feature (Table 3). Further, these distributions may be observed for each canopy type. Our results indicate that right-angle errors for linear features field digitized with GPS should average approximately 5 to 7 metres under a range of closed forest canopies common to eastern North America. In addition, 5 percent of the points recorded will have errors greater than 10 to 18 m after differential correction, depending on canopy type, and 1 percent of the points will have errors greater than 20 to 29 m. Although these proportions are small, they are likely to occur when digitizing all but the most simple linear and area fea-

Table 2. R-Squares from Regression Analysis Indicating Proportion of Variation Attributable to Each Variable, when Compared to the Full Model

| Variable | $R^2$ attributed to each variable |
|---|---|
| PDOP | 0.089 |
| Number of Position Fixes | 0.054 |
| Terrain | 0.008 |
| Canopy | 0.106 |
| Full Model with all Variables | 0.253 |

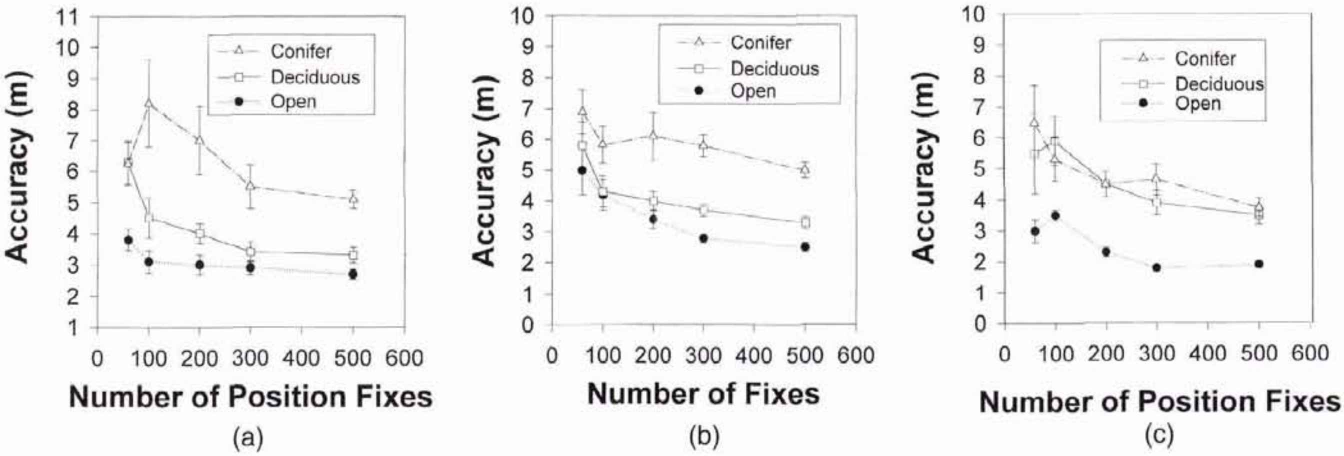


Figure 1. Accuracy of position data for (a) valley, (b) midslope, and (c) ridgetop sites, for each canopy type. Each point represents 30 site visits: three separate sites replicated for ten visits each. Bars depict 1 standard error.

tures. For example, digitizing multi-hectare tracts or a few kilometres of trail on foot generally takes from one-half to a few hours. At a collection rate of one fix per second, one-half hour would result in approximately 18 points with errors in the 20- to 30-m range, and 90 in the 10- to 18-m range.

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 4. The mean PDOPs at deciduous sites were better than those observed at conifer sites. Tukey's standardized range test found the mean PDOPs for each canopy type were statistically different at the $\alpha = 0.05$ level. This suggests that the denser canopies caused the selection of a set of satellites with a poorer PDOP than those in the less dense canopies. The best average PDOPs were observed at open sites.

Differential correction was attempted on a total of 1487 files collected under the diverse conditions in this study. Ninety-four percent of the files were successfully corrected. 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 six-channel receivers. Current 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.

An important consideration for resource managers is the time spent collecting field data. The ANCOVA 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 5). 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 conifer sites was 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. Times for each number of position fixes at open sites were significantly different from all the other position fixes. The mean time to lock (observe four satellites and begin data collection) 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.

Table 3. The Summary Statistics for an Individual Position Fix (No Averaging) for Each Forested Terrain Combination. A Total of 4000 Individual Position Fixes Were Collected from Approximately Twenty Visits to Each Site/Slope Combination. PDOPs Ranged from 2.9 to 6.7 with the Mean of 4.75.

| | Ridge Hardwood | Ridge Conifer | Valley Hardwood | Valley Conifer |
|---|---|---|---|---|
| Mean (m) | 8.4 | 7.8 | 8.5 | 11.3 |
| Std. Dev. (m) | 6.7 | 6.4 | 6.2 | 9.1 |
| 90 Percentile (m) | 16.7 | 13.4 | 16.5 | 22.1 |
| 95 Percentile (m) | 22.9 | 16.5 | 20.3 | 29.1 |
| 99 Percentile (m) | 32.9 | 28.7 | 30.9 | 45.6 |

Table 4. Mean PDOPs for Each Forest and Terrain Type Combination. Each Combination Represents a Sample Size of 150: Three Sites Visited Ten Times and Five PDOP Readings Taken at Each Visit.

| | Canopy Type | | |
|---|---|---|---|
| Terrain | 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 |

Table 5. 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 That Signals from the Satellites Were Interrupted.

| Number of Position Fixes | Minimum time to collect fixes at 1 per second (minutes) | Observed time Deciduous Sites (minutes) | Observed time Conifer Sites (minutes) | Observed time 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 |

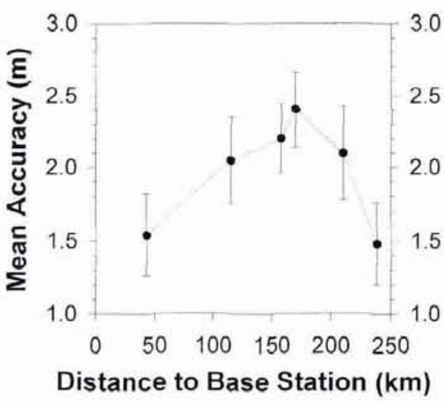


Figure 2. Mean accuracy with increasing distance from a base station. Each point represents the mean difference of NGS versus GPS-determined position. Means were based on nine samples of 300 position fixes for each point, collected over NGS first- and second-order control points, with unobstructed sky conditions.

The ANCOVA results indicated no significant factors affecting the time to lock. Mean lock time 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 $\alpha = 0.05$ level.

We note one important observation made during the course of data collection under forest canopies. We used an antenna mounted on an adjustable-height pole while operating sub-canopy. Our general rule was to adjust antenna height if we encountered a 10-second lull in fix collection. We were often able to increase speed of collection and increase the number of satellites, at times reducing PDOP, by adjusting antenna height during data collection. Although we did not specifically test collection times with a fixed versus adjustable height antenna, we believe this saved considerable time in sub-canopy data collections.

Although there was an observed general degradation in differentially corrected positional accuracy with increasing distance from the base station, the farthest point also exhibited the highest accuracy (Figure 2). Mean accuracy ranged from 1.48 metres at the farthest site to 2.43 metres at the site 169 kilometres from the base station. Tukey's Studentized Range test found that there were no differences among the mean accuracies for each distance study site. PDOPs were not a major factor affecting these distance comparisons. Although there was not a significant difference among the means, there was the appearance of decreasing accuracy with distance from the base station in all but the most distant plot. The majority of accuracies that occurred at each site were in the one- to two-metre range.

## Conclusion

The number of position fixes significantly affected positional accuracy of differentially corrected GPS positions. Three- to seven-metre 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. There was a major difference between position collection times among canopy types. Collection times were nearly twice as long under conifer canopies when compared to open sites. Collection times for deciduous sites were midway between those of open and conifer sites.

Distances of 240 kilometres or less did not significantly affect positional accuracy, at least under clear-sky conditions as tested in this study. Mean accuracies for differentially corrected position data collected within 240 km of a base station were ranged from 1.48 m to 2.43 m.

It appears that the utility of GPS is still available when working under forest canopies and in mountainous terrain, at least under eastern forest conditions. Sub-canopy use and work in steep terrain requires longer occupation times to obtain the same accuracies as when collecting under open skies. However, the time differences are likely to be small for many applications, on the order of 10 minutes a point, and are likely to be insignificant when compared to other costs, such as travel time to sites and system setup, other data collection, and post-processing. Although we expected an increase in ability to collect points in steep versus flat terrain, and an increase in the the number of files which would not differentially correct, we did not observe this in our study.

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