# EFFECTS OF DIFFERENTIAL CORRECTION ON ACCURACY OF A GPS ANIMAL LOCATION SYSTEM

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*Abstract:* The location error of uncorrected data from Global Positioning System (GPS) collars range from ca. 45.5 to 65.5 m (Rempel et al. 1995). Improvements that potentially could reduce locational error to <10 m include correcting systematic bias by reference to GPS data collected at a known position (differential correction), increase in the proportion of positions based on ranging 4 rather than 3 satellites (3-dimensional mode), and increase in the proportion of positions based on a well-spaced satellite configuration (low dilution of precision). Design changes meant to achieve these results were implemented in the second generation GPS collars we evaluated (Lotek Eng. Inc. 1996). We tested the performance of these collars under the controlled canopy conditions of the Thunder Bay experimental forest. Differential correction caused location error to decrease from 80 to 4 m ($P < 0.0001$), and the range of 25–75th percentile location error to decrease from 74.3 to 5.0 m. Location error among sample sites was greatest under tall red pines (*Pinus resinosa*; 15.7 m), possibly because the tall trunks interfered with signal reception, resulting in the acceptance of either 2-dimensional mode positions or positions based on poor satellite configuration (high dilution of precision), or because of multipathing effects caused by signal bounce off the tree trunks. Implementation of differential correction may involve substantial costs to maintain a GPS basestation and data handling, so effectiveness of this enhanced technology must be judged against study objectives and data requirements of the hypotheses being tested.

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**Key words:** *Alces alces*, animal tracking, differential GPS, Global Positioning System, GPS, habitat use, location error, moose, Ontario, satellite telemetry

In a previous study, Rempel et al. (1995) evaluated the performance of a GPS animal location system under controlled canopy conditions in an experimental forest. Although the locational error of 40–60 m reported in that study was much lower than the errors reported by users of the Argos satellite system (Keating et al. 1991) certain design improvements were noted that potentially could reduce locational error to <10 m (Rempel et al. 1995, Rodgers et al. 1996). These included: (1) adjusting position estimates through differential correction; (2) increasing the proportion of 3-dimensional mode over 2-dimensional mode positions; and (3) increasing the proportion of positions based on lower dilution of precision values.

Design changes meant to achieve these results were implemented on GPS tracking collars (Lotek Eng. Inc. 1996). We evaluated the performance of these collars under the controlled canopy conditions of the Thunder Bay experimental forest (Rempel et al. 1995). We show that differential correction greatly enhances the accuracy and precision of locations. The best results were obtained when locations were based on readings from 4 well-spaced satellites. Errors of location were highest in red pine forests.

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## STUDY AREA AND METHODS

We assessed accuracy of differentially-corrected data from GPS collars in the Thunder Bay experimental forest, located northwest of Lake Superior (48°22′N, 89°23′W). The forest was established in 1951, and consisted principally of 3 species: black spruce (*Picea mariana*), white spruce (*P. glauca*), and red pine at regular spacing densities of 1.8, 2.7, and 3.6 m. One site of jack pine (*P. banksiana)* was sampled at 1.8-m spacing. We used 9 sites in evaluating-GPS collars, including 8 forested and 1 open sky site (Table 1).

True location of the sample stations was established through a conventional geodetic survey to GPS observation locations (i.e., sample sites), with line-of-sight transects to a network of existing certified second order horizontal controls to the north, south, east, and west of the experimental forest. Based on accuracy standards for the Province of Ontario (Energy, Mines, and Resour. Can. 1978; Ont. Minist. Nat. Resour. 1979), survey precision in the adjusted NAD83 coordinate system met or exceeded third order accuracy (Rempel et al. 1995).

The antenna for the GPS basestation was located at Lakehead University, Thunder Bay, Ontario, ca 25 m aboveground and 10 km east of the study area. Location of the basestation antenna was established with a geodetic survey with carrier-phase GPS instruments. Certified first and second order horizontal control points to the north, south, and west of the basestation were occupied simultaneously with the basestation with 4 Leica instruments to establish the basestation location at second order accuracy (M. Goadsby, Off. Surveyor General of Ontario, pers. commun.).

At each sample site, tree species, height, basal diameter, percent canopy cover, and spacing were recorded (Rempel et al. 1995). The GPS collars were placed 1.5 m aboveground on a wooden stake adjacent to the iron bar survey marker. Collars were programmed specifically for this study to record locations every 5 minutes. This version of the collar records data with the information necessary to perform differential correction: location, satellite range errors, satellite constellation, horizontal dilution of precision (HDOP), convergence, and time are recorded in the data structure (Lotek Eng. Inc. 1996, Rodgers et al. 1996). Dilution of precision is recorded as HDOP for both 2-d and 3-d modes. We recorded synchronized code-phase measurements at the GPS basestation using a Trimble Community Basestation, which records data in a proprietary data format. Satellite range errors were recorded every 5 seconds. Data were subsequently converted to the RINEX format required by the N3 differential correction program (Lotek Eng. Inc. 1996).

We determined location error as the Euclidean distance of the observed location from the true location,

$$\text{location error} = \sqrt{(\Delta x^2 + \Delta y^2)}$$

where $\Delta x$ and $\Delta y$ = distance in meters from the ground-truthed UTM position for the easting and northing. Exploratory analysis revealed that both location error and HDOP are log-normally distributed, so these measurements were $\log_e$ transformed before parametric statistical analysis. The averages of location error reported are geometric means, i.e., the back-transformed means of location error, and consequently are equivalent to the median location error.

We tested the hypotheses that: (1) differential correction had no effect on location error using analysis of variance (ANOVA), and calculated location error percentiles to explore the effect of differential correction on location error and variance of location error among sample sites; (2) canopy characteristics (species and spacing) had no effect on location accuracy using ANOVA; (3) location error was equal among spruce forest, pine forest, and open forest using ANOVA and Duncan's contrast of control versus all other groups; (4) location error of data collected in 2-d mode was the same as that collected in 3-d mode using ANOVA, and explored this relation by plotting regressions of location error versus HDOP separately for 2-d and 3-d modes; and (5) the odds of obtaining any position and the odds of obtaining a 3-d position were equal regardless of canopy characteristics, using logistic regression and the Wald $\chi^2$ test statistic.

Logistic regression analyzes the odds of an event ($P/[1-P]$), or more precisely, the logarithm of the odds of a binary response variable (e.g., a successful GPS fix), as a function of independent variables (Demaris 1992). Categorical variables were assigned to sample sites for logistic analysis: 4 categories of height (0, 9.7–10.3, 12.7–13.3, and 15.0–16.3 m), and 4 categories of spacing (0, 3.6, 2.7, and 1.8 m; Table 1). In all cases the open canopy site was the reference category. Because of redundancy of information among classes, neither percent canopy cover nor basal diameter were included in the final model. Final logistic models were selected with the forward procedure, with parameter solutions based on maximum likelihood estimates. Odds ratios for individual variables are based on those variables (categories) remaining in the model, and all significant ratios are reported for each analysis.

## RESULTS

Differential correction of GPS determined positions resulted in lower location error ($F$ = 4413.0; 1, 551 df; $P < 0.0001$), with median location error decreasing from 79.5 to 4.2 m (Table 1). With application of differential cor-

Table 1. Canopy characteristics and location errors for differentially corrected and uncorrected positions at sample sites in the Thunder Bay experimental forest, Ontario, 1995.

| | | | | | | Percentiles of location error (m) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Differentially corrected | | | | Uncorrected | | | |
| Species | Site | Tree spacing (m) | % canopy | Height (m) | Basal diam. (cm) | 25th | Median (50th) | 75th | 95th | 25th | Median (50th) | 75th | 95th |
| Red pine | 1017 | 1.8 | 88.9 | 16.3 | 15.7 | 4.2 | 6.9 | 12.0 | 38.5 | 57.4 | 80.6 | 169.2 | 279.0 |
| Red pine | 1013 | 2.7 | 85.3 | 13.3 | 19.3 | 3.4 | 5.4 | 8.2 | 13.1 | 66.2 | 113.7 | 162.8 | 269.7 |
| Red pine | 1015 | 3.6 | 83.0 | 15.0 | 27.0 | 2.5 | 5.4 | 8.9 | 21.9 | 84.6 | 117.3 | 197.3 | 365.0 |
| Jack pine | 1020 | 1.8 | 84.3 | 12.7 | 18.3 | 3.1 | 4.7 | 7.5 | 26.2 | 47.5 | 66.8 | 94.2 | 940.9 |
| Black spruce | 1011 | 2.7 | 89.1 | 13.0 | 16.3 | 2.2 | 4.0 | 5.4 | 15.4 | 66.3 | 107.4 | 162.8 | 341.2 |
| Black spruce | 1016 | 3.6 | 85.2 | 9.7 | 19.7 | 1.9 | 3.6 | 6.4 | 29.4 | 42.9 | 65.0 | 93.4 | 378.5 |
| White spruce | 1012 | 2.7 | 92.6 | 12.7 | 23.0 | 2.7 | 4.3 | 8.6 | 16.7 | 48.6 | 57.6 | 139.1 | 749.5 |
| White spruce | 1014 | 3.6 | 84.0 | 10.3 | 22.7 | 2.6 | 4.0 | 5.2 | 10.8 | 51.6 | 78.1 | 127.5 | 239.6 |
| Total forested | | | | | | 2.8 | 4.7 | 8.2 | 21.6 | 51.6 | 82.0 | 132.4 | 317.1 |
| Open canopy | 1002 | | | | | 1.5 | 2.6 | 3.6 | 7.5 | 44.4 | 57.2 | 87.9 | 125.6 |
| Total all sites | | | | | | 2.6 | 4.2 | 7.6 | 20.9 | 51.4 | 79.5 | 125.5 | 290.1 |

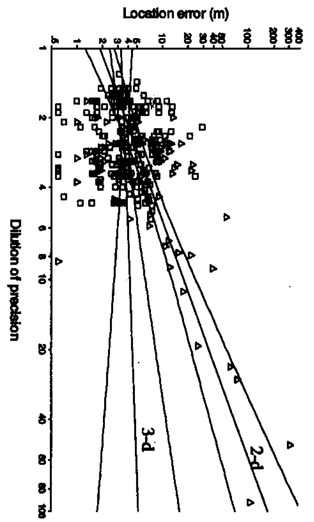

Fig. 1. Global Positioning System location error and recorded horizontal dilution of precision (index of position quality) for data collected in Thunder Bay experimental forest, Ontario, 1995. Least-squares regression line and associated 95% confidence limits for the slope are based on log-transformed location error. Square symbols represent data collected in 3-dimensional mode, with ranging to 4 satellites, and triangles are data collected in 2-dimensional mode, with ranging to 3 satellites.

rection, variability in location error, described as the range of 25–75th percentile, decreased from 74.1 to 5.0 m. Location error varied among sample sites ($F = 4.2$; 8, 267 df; $P < 0.0001$); all forested sites had higher location error than the control site, and red pine (1.8 spacing) had higher error than black spruce and white spruce for both 3.6- and 2.7-m spacing.

Location error was higher ($F = 29.6$; 1, 275 df; $P < 0.0001$) for positions determined in 2-d (6.7 m) than 3-d mode (3.6 m). Regressions of location error with HDOP reveal that location error is related to HDOP in 2-d mode ($r^2 = 0.47$; 1, 85 df; $P < 0.0001$) but not 3-d mode ($r^2 = 0.0001$; 1, 189 df; $P = 0.87$; Fig. 1). Location error of positions with HDOP $\leq 5$ was lower (3.9 m) than positions with higher HDOP values (20.1 m) ($F = 74.1$; 1, 275 df; $P < 0.0001$). For positions with HDOP $\leq 5$, 3-d position errors were still lower than 2-d position errors ($F = 7.95$; 1, 255 df; $P = 0.0052$), but the magnitude of difference was relatively small (3.6 and 4.9 m, for 3-d and 2-d positions). For 2-d mode, the predictive log-linear model of location error based on HDOP is:

$$\text{Log}_e \text{ (location error)} = 0.944 (\log_e \text{HDOP}) + 0.638.$$

In contrast with the open canopy site, the odds of not obtaining any GPS position was higher only at the greatest tree heights (15.0–16.3 m)(Wald $\chi^2 = 13.5$, 1 df, $P = 0.0002$), with odds of not obtaining a position increasing 3.8 times for this category. The odds of obtaining any GPS position did not differ from the open canopy reference site with the other categories

Table 2. Global Positioning System observation rates for sample sites in the Thunder Bay experimental forest, Ontario, 1995.

| Species | Spacing (m) | Height (m) | No. GPS obs. Max. possible | No. GPS obs. Total successful | No. GPS obs. 3-d | GPS obs. rate Total | GPS obs. rate 3-d |
|---|---|---|---|---|---|---|---|
| Red pine | 1.8 | 16.3 | 35 | 28 | 13 | 0.80 | 0.46 |
| Red pine | 2.7 | 13.3 | 35 | 31 | 20 | 0.89 | 0.65 |
| Red pine | 3.6 | 15.0 | 34 | 24 | 6 | 0.71 | 0.25 |
| Jack pine | 1.8 | 12.7 | 34 | 33 | 28 | 0.97 | 0.85 |
| Black spruce | 2.7 | 13.0 | 35 | 33 | 19 | 0.94 | 0.58 |
| Black spruce | 3.6 | 9.7 | 34 | 30 | 24 | 0.88 | 0.80 |
| White spruce | 2.7 | 12.7 | 33 | 31 | 24 | 0.94 | 0.77 |
| White spruce | 3.6 | 10.3 | 35 | 31 | 22 | 0.89 | 0.71 |
| Total forested | | | 275 | 241 | 156 | 0.88 | 0.64 |
| Open canopy | | | 35 | 35 | 34 | 1.00 | 0.97 |
| Total all sites | | | 310 | 276 | 190 | 0.89 | 0.68 |

of tree heights or spacings. The success rate of obtaining any GPS position varied from 71 to 97% under the various canopy conditions, and was 100% under open sky. Under all conditions, success rate was 89% (Table 2).

In contrast with the open canopy reference site, the odds of obtaining a poorer quality 2-d position versus a better quality 3-d position increased 10.5 times at the greatest tree heights (Wald $\chi^2 = 34.5$, $P < 0.0001$), 3.0 times at the 3.6 m spacing (Wald $\chi^2 = 7.9$, $P = 0.0049$), and 4.9 times at the 2.7 m spacing (Wald $\chi^2 = 14.5$, $P < 0.0001$).

## DISCUSSION

Differential correction of GPS data improved both the accuracy and precision of positions, lowering both the magnitude and variability of location error. Median error of the differentially corrected data was 4.2 m, which is almost identical to the 4.1 m error reported by August et al. (1994) in their study of hand-held GPS units (Trimble Pathfinder Basic™). Considerable improvement in the reliability of the position estimates can also be made if positions with HDOP >5 are excluded, and because 93% of the positions are with HDOP ≤5, only a small proportion of data would be excluded for the added reliability.

In terms of wildlife applications, canopy characteristics have only a marginal effect on location error because the variability in accuracy among canopy types is not much greater than the length of a moose (*Alces alces*). Much of the improvement can be attributed to the effect of tall pine trees on limiting the ability of the collar to acquire a signal from a suitable satellite constellation. As in the previous study of undifferentially corrected GPS collars (Rempel et al. 1995), sample location under tall red pine had the poorest performance, even though the canopy was more open than the dense black spruce and white spruce stations. Again, we speculate that the long pole-like trunks of the red pine cause interference with signal reception, causing the receiver to either accept a 2-d position, or satellite configuration with a high DOP value. Poor dispersion of satellites (clustered) results in poor triangulation and low predicted quality of position, while high dispersion of satellites results in better triangulation and higher quality position estimates. Signal interference causes only a subset of the 6–8 satellites usually visible to be available to the receiver, hence the possible selection of a poor satellite configuration.

Other research has similarly concluded that sub-optimal satellite configurations is the cause of lower accuracy under canopy. In their study of GPS under eastern forest conditions, Deckert and Bolstad (1996), found location errors of 5.9, 6.6, and 3.9 m in deciduous, conifer, and open sites. In a study to simulate the effect of canopy interference on location accuracy, Moen et al. (1996) progressively reduce the number of available satellites with differential processing software, and conclude that reduced satellite availability is the cause for increased location error under canopy.

The possibility that multipathing effects (i.e., signal interference caused by signals arriving at the receiver via 2 or more paths) degrade position accuracy under canopy cannot be discounted. However, Wells (1990) suggests that these effects are likely to be limiting factors only at the higher levels of accuracy (e.g., pseudorange applications at the 10 m level and carrier phase applications at the cm level). Highly reflective environmental surfaces such as rock faces and smooth bark may degrade accuracy, but this issue requires further research to identify the prevalence and magnitude of the problem, and the contribution of antenna design to multipathing problems.

Although accuracy was lower at the intermediate density spruce sites (4.1 m location error), it is within 2 m of the error for the open canopy site. Canopy at some of the spruce stations was dense with little light reaching the forest floor, but this dense layer of needles and branches did not seem to interfere with the 20-cm GPS code signal (Wells 1986), and the ability to achieve reasonable location accuracy.

These GPS receiver collars performed better in several ways than those reported on earlier (Rempel et al. 1995). That study revealed the relative quality of 3-d versus 2-d positions for undifferentially corrected data, and provided a predictive model of location error based on HDOP. The linear model presented in Rempel et al. (1995) was encoded in the firmware of the present version of the collars, and used to optimize effort (seek-time) in obtaining positions with acceptable HDOP (D. Cramer, Lotek Eng. Inc., pers. commun.). Based on the earlier reported results, firmware was also changed to allot more time to attempt a 3-d mode position.

Changes in GPS firmware also have resulted in decreased influence of canopy on signal reception. The overall success-rate of signal acquisition has increased from 71% (Rempel et al. 1995) to 89%, and the lowest success rate of 71% reported here was higher than the previous low of 10% observed under red pine. The potential effect of habitat bias has been reduced, but not eliminated with the design modifications implemented in this version of the GPS animal location collar.

## MANAGEMENT IMPLICATIONS

We demonstrated that location error of differentially corrected GPS collar data is substantially lower than undifferentially corrected data. There are substantial costs, however, involved with implementing differential correction. A GPS basestation must be active and maintained continuously, with systems-staff effort devoted to file maintenance, downloading, backup, archiving, and differential file processing. At the longest recommended measurement interval of 5 seconds, ca 0.25 megabytes (MB) of data and 24 separate GPS basestation files are created daily, resulting in ca 186 MB of data monthly. The basestation should be located no more than 400 km from the GPS collars, with performance and success of differential correction decreasing with greater distances; thus some studies may require more than one basestation. The greater amount of information required for differential correction means less memory is available on the GPS collars to store positions, therefore more frequent downloads, and hence greater power demands are put on the collars. Battery-life expectancy will likely decrease.

These negatives must be balanced against the gains of differential correction. Location error decreases from ca 80 to 4 m, and variability decreases (hence reliability increases) for the accuracy of individual measurements. The decision to invest in the additional cost of differential correction capability, and indeed, the decision to invest in GPS collar technology at all, depends on the objectives of the study and data requirements of the hypotheses being tested. These must be matched carefully against the available technology to decide on the relative cost effectiveness of differential correction capability for GPS collars. For example, tests of hypotheses concerning the use of fine scale habitat features will have more analytical power if positions are located with ca. twice the accuracy of the habitat map resolution. Habitat maps derived from Landsat TM imagery have a maximum resolution of 25 m, hence 10 m positional accuracy provided by differential GPS will increase hypothesis testing power.

In contrast, tests of hypotheses concerning home range size will gain relatively more power by increasing sample size rather than decreasing location error through differential GPS. As differential GPS affects battery longevity and maximum number of positions stored on the collar, an a priori decision of which hypotheses are to be tested is required to implement the optimal GPS data collection strategy.

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# ACCURACY OF GPS TELEMETRY COLLAR LOCATIONS WITH DIFFERENTIAL CORRECTION

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*Abstract:* Global Positioning System (GPS) units in telemetry collars provide an unbiased and precise estimate of animal locations. Under ideal conditions at least 50% of locations are expected to be within 40 m in uncorrected mode GPS, and within 5 m in differential mode GPS. When the collar was placed under open sky, most locations were 3-dimensional locations that could be differentially corrected. Under hardwood canopies with leaves on, the frequency of 3-dimensional locations decreased, the frequencies of failed location attempts and 2-dimensional locations increased, and the precision of GPS locations decreased. We compared the precision of each GPS mode by calculating uncorrected mode and differential mode locations from the same pseudo-range and ephemeris data. We varied the number of satellites used in the location solution to simulate the effect of decreased satellite acquisition due to canopy cover on precision of locations. Precision of locations increased if signals from >4 satellites were used to calculate the location in uncorrected mode and in differential mode. We found that 2-dimensional locations were almost as precise as 3-dimensional positions if the altitude of the GPS unit was known. If the altitude used to calculate a 2-dimensional location was within 50 m of the actual collar altitude, the precision of 2-dimensional differential mode locations was better than 3-dimensional uncorrected mode locations. If the error in altitude was 100 or 150 m, then 50% of 2-dimensional differential mode locations were within 70 m and 95% were within 185 m of the true location. We used GPS locations from collars placed in different cover types and on free-ranging moose (*Alces alces*) to determine the effect of season, time of day, rainfall, and cover type on GPS performance. On free-ranging moose the collar GPS unit found ≥4 satellites on 52% of location attempts, >50% of locations were 3-dimensional, and >24% of locations were 2-dimensional. Precise tracking of individual animals in all weather throughout the year is possible with GPS telemetry.

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**Key words:** *Alces alces*, bias, differential correction, Global Positioning System, GPS, moose, precision, radiotelemetry, rain, satellite availability, summer, winter

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With the advent of new technologies in radiotelemetry, such as GPS collars, it is important to determine precision and test for biases of locations reported by the collars. Inaccurate locations may result in false acceptance or rejection of hypotheses, which could lead to incorrect conclusions regarding habitat use by collared animals. Because the animal moves