GPS radiotelemetry error and bias in mountainous terrain

Robert G. D'Eon, Robert Serrouya, Graham Smith, and Christopher O. Kochanny

Abstract Radiotelemetry methods using global positioning system (GPS) technology are becoming increasingly popular, but raw data obtained from these methods contain error and bias that must be addressed. We deployed GPS radiocollars at fixed locations in mountainous terrain across a range of canopy cover and terrain conditions using nondifferentially corrected GPS data to test a hypothesis that these factors affect fix rates and location error in a predictable manner. Terrain did not affect fix rates in forest openings but interacted with canopy cover, resulting in lower fix rates as canopy cover increased. Horizontal differences between recorded locations and associated true locations were 5.9 m and 30.6 m, respectively, for 50% and 95% circular error probable (CEP). Absolute differences between recorded elevations and associated true elevations were 22.9 m and 54.6 m, respectively, for 50% and 95% CEP. We rejected time of day as an influence on fix rates and found that collar performance was a large potential source of error. We recommend that raw GPS radiotelemetry data be screened for collar malfunctions and impossible data (e.g., a location beyond the possible range of a study animal) prior to analysis. We suggest that error in GPS radiotelemetry data could be decreased by considering rejection of 2-dimensional fixes, but doing so could introduce additional biases and must be done with caution, if at all. Fix-rate bias may potentially be addressed with correction factors if predictable relationships between fix rates and environmental factors exist.

Key words available sky, British Columbia, canopy cover, elevation error, fix rate bias, GPS radiotelemetry, location error

Wildlife radiotelemetry methods using global positioning system (GPS) technology are becoming increasingly popular because of the obvious advantages of automated tracking of animal movements. However, raw data acquired through GPS radiotelemetry systems contain bias and error that must be addressed to arrive at accurate conclusions (Rempel et al. 1995; Moen et al. 1996, 1997; Rempel and Rodgers 1997; Dussault et al. 1999, 2001; Bowman et al. 2000). Using built-in GPS and digital storage components, GPS radiocollars automatically determine GPS positions at set time intervals that are stored and later downloaded by researchers using associated computer software (see Rodgers et al. 1996 for a thorough description). Briefly, a GPS radiocollar contacts GPS satellites orbiting the earth. A minimum of 3 satellites is required to obtain a 2-dimensional (2-D) fix (a fix occurs when a GPS location is successfully obtained). Four satellites are required for a 3-dimensional (3-D) fix, which is more accurate than a 2-D fix (Moen et al. 1996). Satellite acquisition is the most important factor influencing fix-rate success and accuracy of ensuing locations (Moen et al. 1997).

The number of satellites available to a GPS radiocollar can be affected by physical obstructions between the collar and satellites. Results from GPS radiotelemetry evaluations concerning effects of

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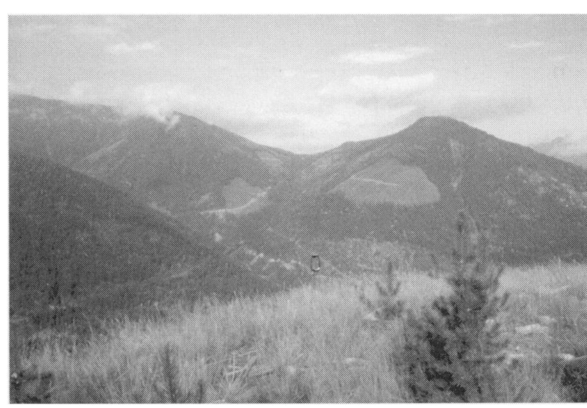
GPS radiocollar sampling site in a partially closed valley-bottom site in winter.

vegetation characteristics on GPS collar performance are mixed (Dussault et al. 1999). However, a general trend toward reduced fix rates and positional accuracy with increasing forest density appears consistent. Openings and clearings have almost universally resulted in higher fix rates and location accuracy than forested sites (Rempel et al. 1995; Moen et al. 1996, 1997; Rempel and Rodgers 1997; Dussault et al. 1999).

To our knowledge, virtually all published accounts of GPS radiocollar performance have occurred in eastern North America in areas of little topographic relief. In the only exception we know, Rodgers et al. (1997) reported mean location errors from GPS radiocollars in the Rocky Mountains of Alberta. As a result, the effects of topography on GPS radiocollar performance are relatively unknown. Dussault et al. (1999) performed an evaluation in eastern Canada in gently rolling terrain with elevations ranging from 250 to 1,050 m with slope gradients up to 60%. While they did not find that topography influenced GPS collar performance, terrain in their study area was not representative of the mountainous regions of western North America where elevations and slope gradients often exceed 2,000 m and 100%, respectively.

Prior to May 2000 the most significant source of error in GPS data for civilian use was attributable to the United States Department of Defense's policy of selective availability (Wells 1986). For reasons of national security, constant and unpredictable sources of error were introduced into satellite transmissions, resulting in a reported GPS location accuracy of 100 m 95% of the time (Wells 1986). Errors in GPS radiotelemetry data introduced by selective availability could be greatly reduced by the process of differential correction (Moen et al. 1997, Rempel and Rodgers 1997). However, in May 2000 selective availability was discontinued. With this major source of error eliminated, reported accuracies and bias in GPS radiotelemetry data prior to this date are likely not reflective of current values. We are not aware of any published accounts of a GPS radiotelemetry evaluation without the influence of selective availability.

We performed a GPS radiotelemetry evaluation in steep mountainous terrain dominated by mature coniferous forests using non-differentially corrected GPS data without the influence of selective availability. We hypothesized that location error and fix-rate bias increase in a predictable manner with increasing obstructions from terrain and vegetation. To test this hypothesis we quantified location error and fix-rate bias of GPS radiocollars under varying terrain and habitat conditions. We also tested the hypothesis that fix rates varied with time of day. Additionally, we investigated general collar



GPS radiocollar sampling site on an open ridgetop. Mountain peak in background was also used as a sampling location.

functioning and methods for minimizing and addressing error and bias in raw GPS radiotelemetry data.

Study area

The study area was located in the Selkirk Mountains of southeastern British Columbia, approximately 23 km northwest of Nelson (49°42′N, 117°25′W; Figure 1). The study area was an approximately 15,000-ha forested mountainous landscape. Elevations within the study area ranged from 548 m at the mouth of Lemon Creek to 2,405-m mountain peaks. Terrain was generally steep and broken, with slope gradients > 100% and slope aspects varying from 1 to 360°.

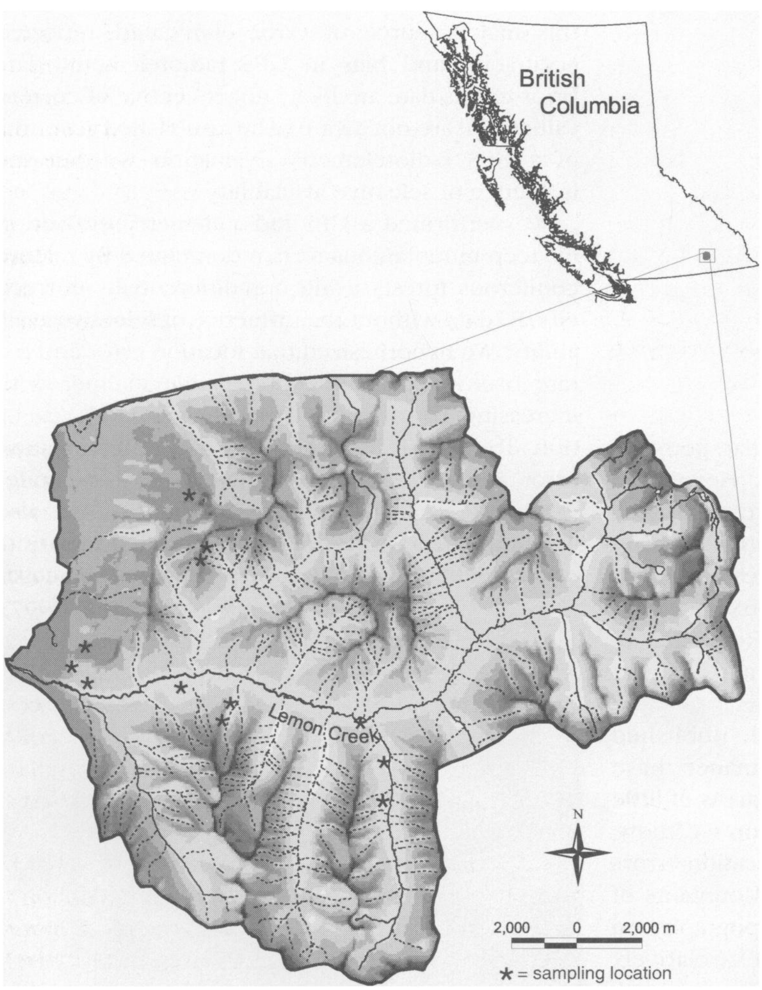


Figure 1. Available sky classification of the Lemon Creek study area for a GPS radiotelemetry evaluation in southeastern British Columbia, 2000–2001. Available sky values range from 0 to 100 % with lighter shades representing low values (valley bottoms) and darker shades representing higher values (ridge tops).

The study area was within the Interior Cedar Hemlock Dry Warm (ICHdw), Interior Cedar Hemlock Moist Warm (ICHmw2), and Englemann Spruce Subalpine Fir Wet Cool (ESSFwc1 and 4) biogeoclimatic zones (Braumandl and Curran 1992). The ICHdw zone occurred from the lowest elevations in the study area to approximately 1,000 m, above which ICHmw2 extended to approximately 1,450 m, above which ESSFwc1 and 4 extended to the treeline at approximately 1,950 m. Forests in ICHdw consisted mostly of mixed seral stands of Douglas-fir (*Pseudotsuga menziesii*), white birch (*Betula papyrifera*), western larch (*Larix occidentalis*), and western white pine (*Pinus monticola*). Forests in ICHmw2 were mostly seral mixes of western hemlock (*Tsuga hetrophylla*) and western redcedar (*Thuja plicata*). Forests in ESSFwc1 and 2 were mostly seral mixes of Engelmann spruce (*Picea engelmanni*) and subalpine fir (*Abies lasiocarpa*). Common shrubs in ICHdw and ICHmw2 were falsebox (*Pachistima myrsinites*), Douglas maple (*Acer glabrum*), and black huckleberry (*Vaccinium membranaceum*). Common shrubs in ESSFwc1 and 4 were white-flowered rhododendron (*Rhododendron albiflorum*) and black huckleberry.

Approximately 97% of forests in this landscape were dominated by coniferous species, with forest canopy closure varying from 0% in clearcuts and natural openings to 100% in dense stands (British Columbia Ministry of Forests, unpublished data). Broad-scale commercial logging in the area began in 1950, resulting in a current landscape of dispersed clearcuts within a mature forest matrix.

Methods

We quantified the influence of terrain on GPS radiocollar performance by creating a variable we called "available sky" (Rodgers et al. 1997). We defined available sky (AS) as the proportion of sky available to a GPS radiocollar through direct line of sight in all directions and at all angles without terrain obstructions (disregarding forest cover). In this way, locations on mountain tops had relatively high AS values due to an unobstructed view of the sky. Conversely, locations in steep valley bottoms had relatively low AS values due to mountain ridges on either side obstructing the view of the sky laterally.

We calculated AS values for all locations in the study area using ARCINFO Grid Module, a raster-based geographic information system (GIS). Using a digital elevation model with 50 × 50-m pixel size that represented the ground, we performed a visibility analysis to model the proportion of sky visible from each pixel location in the elevation model. We used a matrix of points (sky matrix) with 1 × 1-km spacing to represent the sky. We set the altitude of the sky matrix 100 m above the highest location in the study area. For each location on the ground, we determined whether each point in the sky matrix was visible (i.e., direct line of sight unobstructed by terrain). We calculated AS for each ground location as the proportion of the total number of sky matrix points visible from that location (Figure 1).

To evaluate GPS radiocollar performance, we selected 12 locations ranging from 10% to 70% AS (Figure 1). At each location we established 3 sites stratified by canopy cover using the following classes: open (0% canopy cover), partially closed (30–60%), and closed (80–100%). At each site we deployed a radiocollar by attaching it to a stake at approximately 1 m from the ground ensuring that the GPS receiving unit was horizontal. We set radiocollars to attempt GPS fixes at 15-min intervals and left them for 18 to 24 hrs at each site. We activated all radiocollars in a clearing and confirmed they were functioning properly prior to deployment at each site.

We sampled during two periods: once between 9 and 15 October 2000 and again between 5 March and 8 April 2001. We did this to capture summer (deciduous vegetation present) and winter (no deciduous vegetation) conditions. We placed collars in exactly the same spots on the ground during both sample periods. During the summer sample period we used 9 radiocollars circulated among all sites; 3 radiocollars were used in the winter sample (number of collars used was based solely on collar availability). All radiocollars contained a Garmin GPS 25LP receiver (Wildlink 1990) and were obtained from Advanced Telemetry Systems (Isanti, Minn.).

At each site we measured the following habitat attributes: aspect, slope gradient, canopy cover, crown composition, basal area, average tree height, average tree diameter (DBH), horizontal cover, distance to first live branch, GPS position, and elevation. We measured aspect with a compass, slope gradient with an analogue clinometer, canopy cover with a spherical densiometer (Lemmon 1956), basal area with a prism of basal area factor 4, and horizontal cover using a cover pole (Griffith and Youtie 1988). We determined crown composition within a 10-m radius plot. We determined average tree diameter and height by accurately measuring one representative tree in a 10-m radius plot. We measured distance to first live branch as the distance between the top of the GPS receiving unit on a radiocollar to the first live tree branch above it.

We obtained reference positions and elevations with a Trimble GPS Pathfinder Pro XR unit using post-processing differential correction resulting in a reported accuracy of <1.0 m (Trimble Navigation Ltd., Sunnyvale, Calif.). We assumed data from the Trimble unit to be the true location and elevation of each site for analytical purposes. We acknowledge the circularity of using GPS technology to determine the true location for these tests. However, sub-meter accuracy was obtained at each site from the Trimble unit and therefore discounts environmental influences in these data.

Data management and analysis

For each fix a GPS radiocollar stored the date and time of the fix along with the collar location (Universal Transverse Mercator coordinate) and positional dilution of precision (PDOP), a measure of the quality of satellite geometry and an overall estimate of location error precision (Moen et al. 1997). Only successful fixes were stored. If a collar was unsuccessful in obtaining a GPS fix, no record of the event was stored. We calculated fix-rate success by comparing the number of fixes stored in a collar to the maximum possible number of fixes based on the length of time the collar had been deployed at each site.

After all sites had been visited once (i.e., initial 18 to 24-hr period of GPS radiocollar data collection at each site), we downloaded and inspected all stored data. We discovered that most sites had relatively high fix-rate success (>75%), but several had extremely low fix rates (<20%), with some collars recording no data at some sites. We suspected random collar malfunction in cases of no or extremely low fix-rate success. To test this assumption, we redeployed collars at sites with <50% fix-rate success resulting from the first visit. If a subsequent visit resulted in a fix rate >50%, we accepted this as the true fix rate and assumed the results from the previous visit were due to collar malfunction.

We recognized two major sources of error in raw GPS radiotelemetry data: location error and fix-rate bias. We defined location error as the horizontal distance between the location a radiocollar recorded and the associated true location, as well as the difference in elevation between the recorded and true location. We defined fix-rate bias as the likelihood of a radiocollar obtaining GPS fixes given a variety of terrain and habitat conditions. We calculated location error as the Euclidean distance (m) between the coordinates recorded at each fix and our reference coordinates for each site, and elevation error as the absolute value of the difference (m) between the recorded elevation and our reference elevation for each site. We found no significant differences between sample periods in mean location errors ($t_{35}=-1.063$, $P=0.295$), elevation errors ($t_{35}=-0.593$, $P=0.557$), or fix rates ($t_{35}=0.083$, $P=0.934$). On this basis we combined data from both sample periods and used the mean of average fix rates and location errors from both periods to obtain mean fix rates, location errors, and elevation errors for each site.

To test differences among times of day, we stratified the 24-hr clock into 4-hr classes (1=2400-0359 hr, 2 = 0400-0759 hr, 3 = 0800-1159 hr, 4 = 1200-1559 hr, 5=1600-1959 hr, 6=2000-2359 hr). We converted aspect, recorded as a continuous circular variable, to a nominal variable based on solar incidence classes: flat, 60-135°, 136-240°, 241-285°, and 286-59°. Forest types were assigned based on leading tree species as open (i.e., no trees present), western redcedar and western hemlock mix, Douglas-fir and Ponderosa pine (*Pinus ponderosa*) mix, or Englemann spruce and sub-alpine fir mix.

All statistic analyses were performed using SYSTAT 8.0 software (SPSS 1998). Sites ($n=36$) were considered the experimental unit in most cases (Krebs 1999). However, data from individual fixes were also considered independent samples to compare individual 2-D and 3-D fixes and to evaluate the efficacy of PDOP in predicting location error of individual fixes. In doing so we recognized a potential pseudoreplication problem (Hurlbert 1984). However, to investigate means of censoring data on an individual fix basis, and for comparison with past research (Rempel et al. 1995, Moen et al. 1996), we believed this to be a suitable approach in these 2 cases. We used Pearson correlations with associated Bonferroni probabilities to assess correlations between variables, student's two-sample and paired-sample *t*-tests to test differences between means and Welch's approximate t when sample variances were unequal, and χ^2 goodness of fit tests to test differences between distributions (Zar 1984). We used simple and multiple linear and simple curvilinear regression with associated *F*-ratio probabilities to assess relationships among variables (Zar 1984, Tabachnick and Fidell 1996).

For multivariate analyses we screened all variables for normal distributions using skewness and kurtosis indicators which we considered extreme if ± 2 times their standard error did not include zero (SPSS 1998). In one case, average fix rate, we used an arcsine transformation to produce a more normal distribution (Fowler et al. 1998). Discrete variables were included in multivariate procedures using dummy variable coding (Cohen and Cohen 1983).

Results

During the summer sample, 8 of 36 sites resulted in <50% fix rate success (1 of the 8 sites recorded no data) on the first visit and were therefore revisited. All 8 of these sites recorded ≥50% success on the second visit. During the winter sample, again 8 of 36 sites resulted in <50% fix-rate success on the first visit (3 of the 8 sites recorded no data). Seven of the 8 revisited sites in winter resulted in ≥50% success on the second visit; 1 revisited site resulted in <50% success. On the third visit in winter, the remaining site resulted in ≥50% success. We found no correlation among sites that failed on the first visit between sample periods ($r=0.033$, $P=0.848$). Further, we found no significant trends or relationships among sites that failed on the first visit and any terrain or habitat variables collected.

Using final visit data only (i.e., ≥50% fix-rate success), we further identified 5 cases of impossible data (e.g., elevation=19,772 m) that were deleted from analyses. Mean fix rates among the 36 sites ranged from 70.9% to 100% ($\bar{x}=94.7\%$, SE=1.27). Overall fix rates (all fixes combined) did not differ among time of day classes ($\chi^2_5=1.371$, $P=0.927$). Two-dimensional fixes made up 7.6% of all fixes and had higher mean location (Welch's $t_{494}=7.760$,

Table 1. Mean, median and frequency percentiles for location and elevation errors[a] in a GPS radiotelemetry error evaluation in southeastern British Columbia, 2000–2001.

		Location error (m)					Elevation error (m)				
Fix type[b]	*n*	$\bar{x}$ (SE)	50%	95%	99%	100%	$\bar{x}$ (SE)	50%	95%	99%	100%
2-D	487	28.2 (2.45)	12.4	98.5	270.1	601.3	36.9 (2.35)	24.0	66.0	214.6	545.1
3-D	5712	9.1 (0.28)	5.6	26.2	57.9	932.8	27.1 (0.33)	22.9	51.6	195.4	312.6
All	6199	10.6 (0.29)	5.9	30.6	84.4	932.8	27.8 (0.36)	22.9	54.6	197.5	545.1

[a] Location error is the horizontal distance between the stored location in a GPS radiocollar and the true location. Elevation error is the absolute value of the difference between the stored elevation and the true elevation.

[b] 2-D and 3-D = 2 and 3-dimensional fixes. All = 2-D and 3-D combined.

$P \leq 0.001$) and absolute elevation errors (Welch's $t_{505} = 4.155$, $P \leq 0.001$) than 3-D fixes, and higher associated frequency of occurrence percentiles (Table 1). Recorded elevation was above the true elevation in a higher than expected number of all fixes (5,896 out of 6,199 fixes) if the error was randomly distributed below and above the true value ($\chi^2_1 = 5046.24$, $P \leq 0.001$). A significant relationship occurred between mean PDOP and mean location error among sites ($R^2 = 0.667$, $F_{1,34} = 68.076$, $P \leq 0.001$), but not so between mean PDOP and mean elevation error ($R^2 = 0.007$, $F_{1,34} = 39.199$, $P = 0.627$, Figure 2). When fixes were considered individually, there was a weak relationship between PDOP and location error among all fixes ($R^2 = 0.214$, $F_{1,6197} = 1687.405$, $P \leq 0.001$).

For multivariate analyses, we excluded basal area, DBH, and distance to live branch because of high correlation with canopy cover ($r > 0.80$) which violated multicollinearity assumptions (Tabachnick and Fidell 1996). An initial full-model multiple linear regression of average location error against all terrain and habitat attributes provided a significant regression ($R^2 = 0.627$, $F_{13,22} = 2.526$, $P = 0.027$), but did not identify any individual significant predictors (all $P > 0.250$). Using a manual stepwise regression approach, we eliminated noncontributing variables in order of highest *P*-values (Tabachnick and Fidell 1996). This process resulted in a significant regression ($R^2 = 0.431$, $F_{2,33} = 12.479$, $P \leq 0.001$, Figure 3) of average location error against canopy cover and AS, which were both significant predictors ($t_{33} = 3.485$ and -3.056, $P = 0.001$ and 0.004, respectively). This model was: location error = 0.080 × canopy cover -0.144 × AS + 11.691. We found no significant trends or relationships between elevation error and any terrain or habitat variables collected.

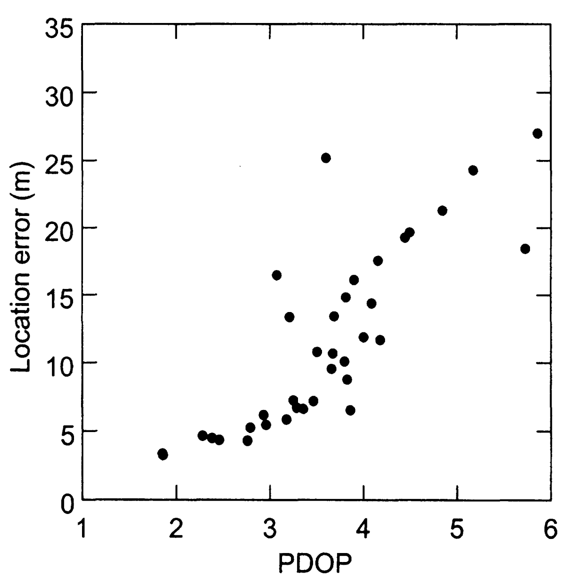


Figure 2. Mean positional dilution of precision (PDOP) versus mean location error ($R^2 = 0.667$, $F_{1,34} = 68.076$, $P \leq 0.001$) for 36 sites within a GPS radiotelemetry evaluation study in southeastern British Columbia, 2000–2001.

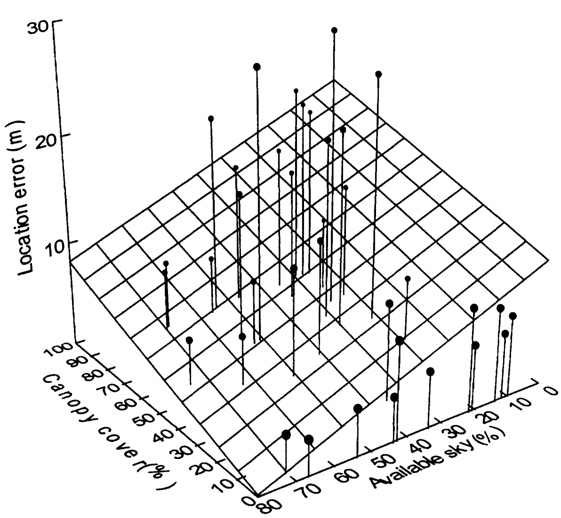


Figure 3. Average location error, canopy cover, and available sky for 36 sites in a GPS radiocollar evaluation study in southeastern British Columbia, 2000–2001. Grid lines represent the plane of best fit from a multiple linear regression of location error against canopy cover and available sky ($R^2 = 0.431$, $F_{2,33} = 12.479$, $P \leq 0.001$). The model is: location error = 0.080 × canopy cover – 0.144 × available sky + 11.691.

Table 2. Analysis of variance for a multiple linear regression of terrain and habitat variables in a GPS radiocollar evaluation in southeastern British Columbia, 2000–2001. Dependant variable is average fix rate (arcsine transformed), $R^2 = 0.525$, $F_{11,24} = 2.407$, $P = 0.035$).

Variable [a]	Sum of squares	df	Mean square	*F*-ratio	*P* [b]
Aspect	0.363	4	0.091	2.232	0.096
Slope gradient	0.001	1	0.001	0.037	0.849
Canopy cover	0.307	1	0.307	7.542	0.011*
Forest type	0.138	3	0.046	1.132	0.346
Available sky	0.294	1	0.294	7.222	0.013*
Elevation	0.011	1	0.011	0.282	0.600
Error	0.976	24	0.041		

[a] Aspect converted to 5-class nominal variable: flat, 60–135°, 136–240°, 241–285°, and 286–59°. Forest type classes: opening, western redcedar and western hemlock mix, Douglas-fir and ponderosa pine, and Englemann spruce and sub-alpine fir mix. Dummy variable coding used for aspect and forest type.

[b] Statistical significance indicated (*) at $\alpha = 0.05$.

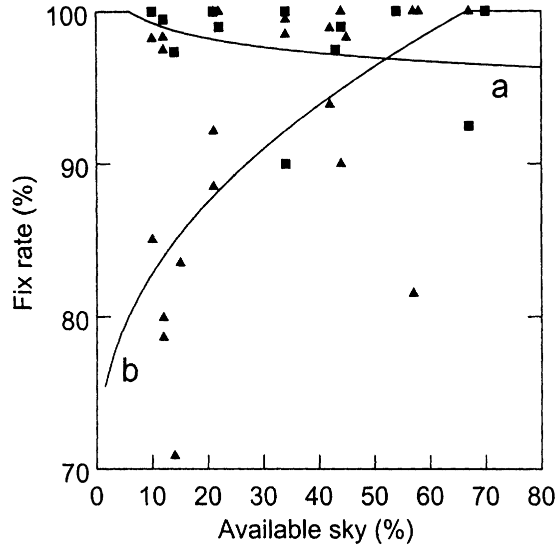


Figure 4. Average fix rates versus available sky estimates for 36 sites grouped by canopy cover in a GPS radiocollar evaluation study in southeastern British Columbia, 2000–2001. Curvilinear regression line (b) indicates best-fit model for the 30 to 100% class ($R^2 = 0.198$, $F_{2,22} = 1641.58$, $P \leq 0.001$). Top line (a) indicates no significant relationship between fix rates and AS in the 0% class ($R^2 = 0.051$, $F_{1,10} = 0.535$, $P = 0.481$). Crown closure class: ■ = 0%; ▲ = 30 to 100%.

In a similar stepwise regression manner, we created a significant multiple linear regression model of average fix rate against terrain and habitat attributes ($R^2=0.525$, $F_{11,24}=2.407$, $P=0.035$, Table 2) by omitting height and horizontal cover based on the most insignificant *F*-ratio values from an initial non-significant full model. We identified only canopy cover ($F_{1,24}=7.542$, $P=0.011$) and AS ($F_{1,24}=7.22$, $P=0.013$) as significant predictors in this model (Table 2). We then created a linear model using only these 2 variables, which resulted in a significant regression ($R^2=0.229$, $F_{2,33}=4.905$, $P=0.014$) with the following equation: Fix rate $= 0.098 \times$ AS $-$ $0.076 \times$ canopy cover $+ 95.363$. As well, because of the low *P*-value ($P=0.096$) attributed to aspect in regression analyses (Table 2), we further investigated possible influences of aspect on fix rate. Despite a somewhat higher mean fix rate for south aspects, differences among aspect classes were not statistically significant (mean fix rates: north $=92.6$ %, $n=11$, SD $=9.1$; east $=93.2$ %, $n=9$, SD $=9.2$; south $=99.9$ %, $n=5$, SD $=0.2$; west $=96.2$, $n=8$, SD $=3.6$; flat $=93.8$, $n=3$, SD $=10.7$; $F_{4,31}=0.951$, $P=0.448$).

To compare openings to partially closed and closed forests, we grouped sites by canopy cover class (0% and 30–100%). We found a curvilinear regression model of fix rate against AS produced a best fit for the 30–100% class ($R^2=0.198$, $F_{2,22}=1641.58$, $P \leq 0.001$), and no significant relationship in the 0% class between fix rates and AS (Figure 4).

Discussion

Whether or not a collar functioned properly was a large potential source of error in our study. We cannot speculate as to the causes of collar malfunctions we experienced and can only state that malfunctions are a part of GPS radiotelemetry at the current state of the technology. We chose to omit data from collars with obvious malfunctions. While we recognize this biases our results, we did this to isolate influences of environmental factors on location errors and fix rates in GPS radiocollar data. Including the influence of collar functioning in these analyses (i.e., retaining data from malfunctioning collars) would not provide meaningful data on environmental influences alone. For example, incorporating into our analyses a fix rate of 0% for a site (presumably due to collar malfunction) would greatly influence our results and be more reflective of collar functioning than environmental influences. We also believe that removing the influence of individual collar performance from our data provided more meaningful results for future studies as technological advances in radiocollar construction result in better collar performance.

By rejecting data from collars with extremely low fix rates, we demonstrated that all of our sites could obtain fix rates >70%, regardless of environmental factors. Merrill et al. (1998), using collars from the same manufacturer, reported that of 11 deployed collars 2 recorded no data, 1 recorded <50% of potential fixes, and 8 recorded >50% of potential fixes. These rates are similar to ours and suggest researchers must account for collar functioning prior to analyzing raw data.

Discontinuing selective availability clearly increased location accuracy of non-differentially corrected data. The United States Department of National Defense's (1984) original expected location accuracy of 40 m at 50% circular error probable (CEP) and 100 m at 95% CEP was increased in our study to 5.9 m and 30.6 m for all fixes, respectively, and 5.6 m and 26.2 m for 3-D fixes, respectively. Our reported accuracy of 5.9 m at 50% CEP for all fixes is similar to ranges reported in Rempel et al. (1997) and Moen et al. (1997) for differentially corrected data. As a result, the discontinuation of selective availability provided similar location accuracy without the need for differential correction.

Average fix rates in our study were comparable to ranges reported for stationary collars in recent studies. However, Moen et al. (1996) and Dussault et al. (1999) reported lower fix rates for collars deployed on free-ranging moose (*Alces alces*), and Bowman et al. (2000) reported lower PDOPs for data from moving white-tailed deer (*Odocoileus virginianus*). This suggests that fix rates can be expected to be lower on free-ranging animals than we report here and more work with free-ranging animals and GPS collar performance is warranted to determine the degree to which animal behavior and movement affect collar performance under varying habitat and terrain conditions.

Two-dimensional fixes made up 7.3% of all fixes in our study. This was lower than 83% reported by Rempel et al. (1995), 74% reported by Moen et al. (1996), and 31% reported by Dussault et al. (1999), and may reflect an improving trend in GPS radiotelemetry technology as suggested by Rempel and Rodgers (1997). This is particularly important since we and others demonstrated that 3-D fixes are more accurate than 2-D fixes and significantly improve overall accuracy of GPS radiotelemetry data (Rempel et al. 1995). On this basis, we suggest that 2-D and 3-D classification may provide a means of censoring raw GPS data to improve overall accuracy.

If a GPS radiocollar is more or less likely to obtain fixes under certain habitat conditions, these habitat types will be over or under-represented in resulting raw data and represent a habitat bias in raw GPS data (Rempel et al. 1995, Dussault et al. 1999). We found that canopy cover and terrain obstruction had significant and predictable effects on fix rates. In openings, fix rates were not significantly different than 100% regardless of terrain attributes, suggesting that terrain obstructions on their own do not significantly affect fix rates. However, when combined with the influence of canopy cover, terrain obstructions had a pronounced effect in partially closed and closed forests. This relationship provides cause for concern, especially when dealing with species or individuals living or traveling in heavily forested valley bottom areas such as riparian areas. Under these habitat conditions we found fix rates as much as 30% lower than in openings and areas of unobstructed terrain. We suggest this habitat bias should be accounted for when analyzing raw GPS data.

Positional dilution of precision provides a measure of location accuracy of reported GPS locations and therefore provides a potential means of censoring raw GPS data. If a predictable relationship between PDOP and location error existed, users could choose to include or omit locations beyond a specific accuracy based on associated PDOP values in raw data. We found a significant relationship between mean PDOP and mean location error among sites, thus supporting this notion. However, predictive power among individual fixes was low, and no predictive relationship between PDOP and elevation error existed. Rempel et al. (1995) and Moen et al. (1996, 1997) similarly found weak relationships between horizontal dilution of precision (HDOP) and location error among individual fixes, and cautioned against its use to censor raw data. On this basis, we also contend PDOP does not provide a strictly quantitative means to censor data, but could be used to evaluate visual cutoffs as suggested by Moen et al. (1996).

One of the advantages of GPS radiotelemetry is 24-hr sampling as opposed to more traditional aerial telemetry methods that yield daylight data only (Beyer and Haufler 1994). We rejected time of day as a source of bias in determining differences in fix rates. Therefore, researchers finding diurnal patterns in fix rates on free-ranging animals can attribute this variability to factors other than those associated with GPS technology and functioning.

From investigation of satellite orbit paths, equatorial-facing aspects are predicted to provide lower dilution of precision that could result in higher radiotelemetry fix rates on these aspects (P. H. Dana, University of Texas, Austin, unpublished data). We did not find statistical differences in mean fix rates among aspect classes, perhaps due to inadequate sample sizes in some aspect classes. Our data, however, suggested slightly higher fix rates on south aspects. We suggest therefore that the influence of aspect bias in GPS radiotelemetry performance should be further tested.

Management implications

We echo Rodger et al.'s (1996) prediction that GPS radiotelemetry will set a new standard for wildlife resource utilization studies. This is especially true if researchers are aware of inherent error and bias in raw GPS data and take steps to minimize and account for these errors. Based on the results of our study and others, we recommend the following steps be taken prior to analyzing raw GPS data:

1. Data from collars with extremely low fix rates (<20%) should be considered suspect, especially if the data are intended for habitat analyses assuming random location sampling. We demonstrated that high fix-rate success (>70%) can be obtained from stationary radiocollars under a wide spectrum of terrain and habitat conditions. While lower fix rates can be expected from radiocollars on free-ranging animals, terrain and habitat attributes should not be attributed as the primary cause of extremely low fix rates, suggesting that other factors such as collar malfunction or animal behavior should be considered. In some cases, however, low overall fix rates could be due to temporal variability in collar functioning where a collar functioned properly for a period of time then became dysfunctional. If this situation can be demonstrated, it may be possible to use portions of the data associated with a specific time frame when the collar was functioning properly.
2. Screen for impossible data. Obvious anomalies representing locations that were not possible for a collared animal to obtain should be rejected.
3. Based on required location accuracy for a specific test or conclusion, it may be possible to omit 2-D fixes to obtain higher location accuracies associated with 3-D fixes. This procedure, however, may introduce additional bias by deleting locations with a lower probability of obtaining 3-D fixes. In our case, since 2-D fixes made up a small proportion of total locations, keeping 2-D fixes may reduce the power of statistical tests, but is preferable to censoring the data and introducing unknown bias. For this reason, we strongly suggest omitting 2-D fixes with caution and only if necessary.
4. If a predictable relationship between fix rates and environmental variables has been established for an area where GPS radiotelemetry data were collected, it may be possible to adjust raw data using correction factors for habitat-use analyses as suggested by Dussault et al. (1999). In this case, expected fix rates and associated correction factors can be assigned to individual locations and associated continuous habitat and biophysical data. As well, adjusted frequencies of occurrence can be calculated for discrete data based on a known fix-rate bias. In this way, weighted averages and frequencies of occurrence, that more accurately reflect true resource use of individual animals, can be calculated.

An important consideration in the analysis of habitat preference using GPS radiocollar data is the use of remotely sensed habitat data in forms such as digital forest cover mapping. In our study, we performed analyses on habitat data that were collected by field crews at each site. This was done to provide the most accurate measure of environmental variables and their influence on GPS radiocollar performance. However, correction factors applied to data derived from remotely sensed habitat data may need to be recalibrated to account for differences between remotely sensed data and field data.

Available sky proved to be an effective method for quantitatively describing terrain obstruction associated with GPS reception and was an important predictor of location accuracy and fix-rate bias. By modeling available sky within a GIS, we were able to calculate its value for any location in our study area. Because AS is a measure of how much sky is available to a GPS receiver, it measures more directly the most important factor in GPS accuracy, satellite availability. We recommend the use of AS anywhere terrain obstruction may affect GPS reception.

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