GPS Radiotelemetry Error and Bias in Mountainous Terrain

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ABSTRACT

Radiotelemetry methods using global positioning system technology are becoming increasingly popular but raw data obtained from these methods contain error and bias that must be addressed. We deployed stationary GPS radiocollars in mountainous terrain across a spectrum of crown closure and terrain conditions to test a hypothesis that these factors affect location error and fix rate in a predictable manner. Results supported our hypothesis. Additionally, we rejected time of day as an influence on fix rates and we found collar functioning was a large potential source of error. Location errors were 5.9 m and 30.6 m, respectively, for 50% and 95% circular error probable, 22.9 m and 54.6 m for elevation errors, respectively. We recommend raw data be screened for collar malfunctions and impossible data prior to analysis. Location error can be decreased by considering rejection of 2-dimensional fixes. Fix rate bias may be addressed with correction factors if predictable relationships between fix rates and environmental factors exist.
INTRODUCTION

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 radio-collar communicates with 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 (on average) 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 vegetation characteristics on GPS collar performance are mixed (Rempel et al. 1995, Dussault et al. 1999). However, a general trend towards 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 topography influenced GPS collar performance, terrain in their study area was not representative of 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 U.S. 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 which resulted in a reported GPS location error 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 since the removal 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 the time of day. Additionally, we investigated general collar functioning and methods for minimizing and addressing error and bias in raw GPS radiotelemetry data.

**STUDY AREA**

The study area was located in the Lemon Creek drainage of 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 where we were executing concurrent GPS radiotelemetry research on mule deer (*Odocoileus hemionus*) movements and habitat use (D’Eon and Serrouya 2001).

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 often exceeding 100% and slope aspects varying from 1 to 360°.

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 ESSFwc4) and alpine tundra (AT) biogeoclimatic subzones (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, then ESSFwc1 and ESSFwc4 to the treeline at approximately 1,950 m, then AT to the highest locations in the study area. 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*); in ICHmw2 forests were mostly seral mixes of western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*); in ESSF forests were mostly seral mixes of Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*). Common shrubs in ICH were falsebox (*Pachistima myrsinites*), Douglas maple (*Acer glabrum*) and black huckleberry (*Vaccinium membranaceum*); in ESSF common shrubs were white-flowered rhododendron (*Rhododendron albiflorum*) and black huckleberry.

Approximately 96.5% 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 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” (AS). We defined AS as the proportion of the sky that was available to a GPS radiocollar through direct line-of-sight in all directions and at all angles without terrain obstructions. 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 (Environmental Systems Research Institute, Redlands, CA). Using a digital elevation model with 50 x 50-m pixel size that represented the ground, we performed a visibility analysis to model the proportion of the sky visible from each pixel location in the elevation model. We used a matrix of points (sky matrix) with 1 x 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 if each point in the sky matrix was visible (i.e., direct line of sight unobstructed by terrain) or not. We calculated AS for each ground location as the proportion of sky matrix points that was visible from that location (Figure 1).

To evaluate GPS radiocollar performance, we selected 12 locations ranging from 10% to 70% AS (Figure 1). We could not sample >70% AS because of limited access to sites. At each location we established 3 sites stratified by crown closure using the following classes: open (0% crown closure), partially closed (30–60%), and closed (80–100%). We used convex spherical densiometers (Lemmon 1956) to measure canopy closure and obtain suitable sites. At each site we deployed a radio-collar 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-minute intervals and left them for 18 to 24 hours at each site. We activated all radio-collars in a clearing and confirmed they were functioning properly prior to deployment at each site.
We replicated the experiment during two periods: once between 9 and 15 October 2000, and again between 5 March and 8 April 2001. We did this to replicate the study during summer (deciduous vegetation present) and winter (no deciduous vegetation) conditions. We placed collars in exactly the same locations during both replications. During the first replication we used 9 radiocollars circulated among all sites, 3 radiocollars in the second replication. All radiocollars contained a Garmin GPS 25LP receiver (Wildlink 1990) and were obtained from Advanced Telemetry Systems (Isanti, Minnesota, USA).

At each site we measured the following habitat attributes: aspect, slope gradient, crown closure, 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, crown closure with a convex 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 estimated 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, CA). We assumed data from the Trimble unit to be the true location and elevation of each site for analytical purposes.
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). We used PDOP rather than HDOP (horizontal precision dilution of precision) because PDOP is a function of HDOP and other sources of error and is therefore a more robust measure of precision. If a collar was unsuccessful in obtaining a GPS fix, no record of the event was stored. We therefore 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, 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 initial 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 recorded by a radiocollar and its 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 failing to obtain GPS fixes given a variety of terrain and habitat conditions. We calculated location error as the euclidian 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 difference between replications in location error ($t_{6199} = -0.233, P = 0.118$), elevation error ($t_{6199} = 1.109, P = 0.267$), or fix rates ($t_{35} = 0.083, P = 0.934$). On this basis we combined data from replications 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 (slope <10 %), 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 statistical analyses were performed using SYSTAT 8.0 software (SPSS 1998). We considered the experimental unit (Krebs 1999:341) to be individual fixes (n = 6,199) when testing parameters related to fixes independent of site attributes. Conversely, to avoid pseudoreplication and inflated sample-size problems (Hurlbert 1984), we used sites (n = 36) as the experimental unit when investigating factors that influenced radiocollar performance at specific sites.
We used Pearson correlations with associated Bonferroni probabilities to assess correlations between variables, student’s t-tests to test differences between means and employed Welch’s approximate t when sample variances were unequal, and chi-square 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 replication, 8 of 36 sites resulted in <50% fix rate success, including 1 with 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 replication, collars at 8 of 36 sites had <50% fix rate success on the first visit, including 3 sites with no data. Collars at 7 of the 8 revisited sites had >50% success on the second visit, but 1 revisited site resulted in <50% success. On the third visit, the remaining collar had >50% success. We found no correlation among sites that failed on the first visit between replications (Pearson $r = 0.033$, Bonferroni $P = 0.848$). Further, we found no significant trends or relationships among sites that failed on the first visit and any terrain or habitat variables we collected (Figure 2).
Using final visit data only (i.e., >50% fix rate success), we further identified 5 cases of impossible data (e.g., elevations that do not exist [e.g., 19,772 m]) that were deleted from analyses. Mean fix rates among final visits at the 36 sites ranged from 70.9% to 100% (\( \bar{x} = 94.7\%, \text{SE} = 1.27 \)). Overall fix rates (all fixes combined) did not differ among time of day classes (\( \text{chi-square} = 1.371, P = 0.927, \text{Figure 3} \)). Two-dimensional fixes made up 7.6% of all fixes and had higher mean location (Welch’s \( t_{494} = 7.760, P < 0.001 \)) and absolute elevation errors (Welch’s \( t_{505} = 4.155, P < 0.001 \)) 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 if the error was randomly distributed below and above the true value (5896/6199, \( \text{chi-square} = 5046.24, P < 0.001 \)). A weak relationship occurred between PDOP and location error (\( R^2 = 0.214, F_{1,6197} = 1687.405, P < 0.001 \)) and no relationship occurred with elevation error (\( R^2 = 0.000, F_{1,6197} = 2.174, P = 0.140, \text{Figure 4} \)).

For multivariate analyses, we excluded basal area, DBH, and distance to live branch because of high correlation with crown closure (Pearson \( r > 8.0 \)) 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 non-contributing variables in order of highest \( P \)-values (Tabachnick and Fidell 1996). This process resulted in a significant regression (\( R^2 = 0.431, F_{2,33} = 12.479, P < 0.001, \text{Figure 5} \)) of average location error against crown closure 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 x crown closure – 0.144 x AS + 11.691. We found no significant trends or relationships between elevation error and any terrain or habitat variables we collected.

In a similar stepwise regression manner we created a significant multiple linear regression model of average fix rate against terrain and habitat attributes \( (R^2 = 0.525, F_{11,24} = 2.407, P = 0.035, \text{Table 2}) \) by omitting height and horizontal cover based on the most insignificant \( F \)-ratio values from an initial non-significant full model. We identified only crown closure \( (F_{1,24} = 7.542, P = 0.011) \) 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 x AS – 0.076 x crown closure + 95.363. To compare openings to partially closed and closed forests we grouped sites by crown closure 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 (Figure 6). In the 0% class we found no relationship between fix rates and AS (Figure 6).

**DISCUSSION**

Whether or not a collar functioned properly was a large potential source of error in our study. 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 that researchers must account for collar functioning prior to analyzing raw data.
The effect of discontinuing selective availability clearly increased the location accuracy of our non-differentially corrected data. The U.S. Department of National Defense’s (1994) original expected location error of 40 m at 50% circular error probable (CEP) and 100 m at 95% CEP was decreased 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. Thus, 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. (2000) 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 (O. virginianus). This suggests that fix rates can be expected to be lower on free-ranging animals than we report here and that more work with free-ranging animals and GPS collar performance is warranted to determine the degree to which animal behaviour and movement affects collar performance under varying habitat and terrain conditions.

Two-dimensional fixes made up 7.3% of all fixes in our study. This is lower than 83% reported by Rempel et al. (1995), 74% reported by Moen et al. (1996), and 30.5% 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 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 of a data set if required.

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 will create a habitat bias in raw GPS data (Rempel et al. 1995, Dussault et al. 1999). We found crown closure 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 crown closure, 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 zones. 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. While we found a significant relationship between PDOP and location error based on a regression $F$-ratio likely due to high sample size, predictive power was low. Further, no predictive relationship between PDOP and elevation error existed. Our findings are consistent with Rempel et al. (1995) and Moen et al. (1996,
1997) who similarly found weak relationships between HDOP (horizontal dilution of precision) and location error, and thus recommended against its use for censoring data (Moen et al. 1996). On this basis we also contend that PDOP does not provide a good means to censor data due to its low predictive ability.

One of the advantages of GPS radiotelemetry is 24-hr sampling as opposed to more traditional 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.

**MANAGEMENT IMPLICATIONS**

We echo the prediction of Rodger et al. (1996) 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 our experience from 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 is 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 behaviour
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 disfunctional. 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. For this reason we strongly suggest
that omitting 2-d fixes be done 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. (2000). Adjusted frequencies of occurrence can be
calculated for discrete habitat classes based on known fix rate biases that more
accurately reflect resource use of individual animals.

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 it 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 its use anywhere
terrain obstruction may affect GPS reception.

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LITERATURE CITED


SPSS 1998. SYSTAT 8.0 for windows. SPSS, Chicago, Illinois, USA.


Table 1. Mean, median and selected frequency percentiles for location and elevation errors\(^a\) in a GPS radiotelemetry error evaluation in southeastern British Columbia, 2000-2001.

<table>
<thead>
<tr>
<th>Fix type(^b)</th>
<th>n</th>
<th>Location error (m)</th>
<th>Elevation error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(\bar{x} (SE))</td>
<td>50%</td>
</tr>
<tr>
<td>2-d</td>
<td>487</td>
<td>28.2 (2.45)</td>
<td>12.4</td>
</tr>
<tr>
<td>3-d</td>
<td>5712</td>
<td>9.1 (0.28)</td>
<td>5.6</td>
</tr>
<tr>
<td>all</td>
<td>6199</td>
<td>10.6 (0.29)</td>
<td>5.9</td>
</tr>
</tbody>
</table>

\(^a\)Location error is the horizontal distance between the stored location in a GPS radio-collar 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.
Table 2. Analysis of variance for a multiple linear regression of terrain and habitat variables in a GPS radio-collar evaluation in southeastern British Columbia, 2000–2001. Dependant variable is average fix rate (arcsine transformed), $R^2 = 0.525$, $F_{11,24} = 2.407$, $P = 0.035$.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sum of squares</th>
<th>$df$</th>
<th>Mean square</th>
<th>$F$-ratio</th>
<th>$P^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect</td>
<td>0.363</td>
<td>4</td>
<td>0.091</td>
<td>2.232</td>
<td>0.096</td>
</tr>
<tr>
<td>Slope gradient</td>
<td>0.001</td>
<td>1</td>
<td>0.001</td>
<td>0.037</td>
<td>0.849</td>
</tr>
<tr>
<td>Crown closure</td>
<td>0.307</td>
<td>1</td>
<td>0.307</td>
<td>7.542</td>
<td>0.011*</td>
</tr>
<tr>
<td>Forest type</td>
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<td>0.046</td>
<td>1.132</td>
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</tr>
<tr>
<td>Available sky</td>
<td>0.294</td>
<td>1</td>
<td>0.294</td>
<td>7.222</td>
<td>0.013*</td>
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<tr>
<td>Elevation</td>
<td>0.011</td>
<td>1</td>
<td>0.011</td>
<td>0.282</td>
<td>0.600</td>
</tr>
<tr>
<td>Error</td>
<td>0.976</td>
<td>24</td>
<td>0.041</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


\(^b\)Statistical significance indicated (*) at alpha = 0.05.
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).
Figure 2. Collar performance at 36 sites varying by crown closure and available sky in a summer (a) and winter (b) repetition of a GPS radiocollar evaluation study in southeastern British Columbia, 2000–2001. Sites are differentiated between those that successfully obtained >50% fix rate success on first visit (first visit success) and those that did not (first visit failure). One standard deviation confidence ellipses are provided to illustrate no significant trends in first visit success or failure (solid lines = first visit success, dashed lines = first visit failure).
Figure 3. Observed and potential (maximum possible) number of fixes by time of day class (4-hr classes beginning at 1 = 2400-0359 hr) for all fixes within a GPS radiocollar evaluation study in southeastern British Columbia, 2000-2001. Fix rates do not differ among time of day classes ($\chi^2 = 1.371, P = 0.927$). Lower sample in class 3 is a result of turning off collars temporarily during mornings to move collars among sample sites.
Figure 4. Positional dilution of precision (PDOP) versus location ($R^2 = 0.214$, $F_{1,6197} = 1687.405$, $P < 0.001$) and elevation error ($R^2 = 0.000$, $F_{1,6197} = 2.174$, $P = 0.140$) for 6,199 fixes within a GPS radiotelemetry evaluation study in southeastern British Columbia, 2000-2001.
Figure 5. Average location error, crown closure 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 crown closure and available sky ($R^2 = 0.431$, $F_{2,33} = 12.479$, $P < 0.001$). The model is: location error = 0.080 x crown closure – 0.144 x available sky + 11.691.
Figure 6. Average fix rates versus available sky estimates for 36 sites grouped by crown closure in a GPS radio-collar evaluation study in southeastern British Columbia, 2000–2001. Curvilinear regression line (b) indicates best fit model for the 30 to 100% class, $R^2 = 0.198$, $F_{2,22} = 1641.58$, $P < 0.001$. Top line (a) indicates no significant relationship between fix rates and AS in the 0% class ($R^2 = 0.051$, $F_{1,10} = 0.535$, $P = 0.481$).