GPS Radio Collar 3D Performance as Influenced by Forest Structure and Topography

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ABSTRACT

Global Positioning System (GPS) telemetry enables biologists to obtain accurate and systematic locations of animals. Vegetation can block signals from satellites to GPS radio collars. Therefore, a vegetation-dependent bias to telemetry data may occur which if quantified, could be accounted for. We evaluated the performance of GPS collars in 6 structural stage categories of 3 forest vegetation types to attempt to quantify the relation between GPS locations and forest vegetation.

INTRODUCTION

Radio telemetry has enabled wildlife biologists to remotely monitor the movements and activities of free-ranging animals in their natural habitats since the 1960s. Locations of animals can be obtained from aircraft, triangulation of radio signals from the ground, or from satellite positioning systems. Triangulation of telemetry signals from the ground and use of aircraft facilitate visual observations of animals. If animals are not seen, their locations from either the ground or aircraft are subject to error and bias (Springer 1979, Lee et al. 1985, Saltz and Alkon 1985, White and Garrott 1990). Bias in locations of animals also occurs if relocation schedules are not random, or if animals are not located because of their activity or the habitat they occupy. Nonetheless, radio telemetry techniques over the past 30 years have proven especially useful in studying the habitat use and selection patterns of wildlife. Thus, experimental designs have been developed that minimize the bias in this application of radio telemetry.

Transmitter collars adapted to animals that measure Doppler shift from satellites (Craighead and Craighead 1987) or Loran-C (Dana et al. 1989) enabled researchers to locate animals in remote locations and during any time period, which enabled greater flexibility in experimental designs than conventional telemetry. Satellite and Loran-C collars also offered solutions to problems associated with locating animals due to vegetation density, topography, darkness, weather, and remoteness (Mech 1983, Rodgers and Anson 1994). Locations obtained with these collars varied from 100 m to 1000 m from the actual location of the animal (Rodgers and Anson 1994), and thus are inadequate for fine-scale studies of animal habitat (Rempel et al. 1995).

The most recent advance in telemetry techniques is the incorporation of a Global Positioning System (GPS) unit in a radio telemetry collar for animals (Rodgers and Anson 1994, Rempel et al. 1995). The Navigation Satellite Time and Ranging (NAVSTAR) GPS is a satellite-based navigation system consisting of 24 high earth-orbit satellites located in 4 orbital planes. GPS radio telemetry incorporates the advantages of Loran-C and Doppler shift satellite telemetry systems and is more accurate.

GPS receivers operate on a line-of-sight principle. Successful locations depend on satellite visibility and may be affected by animal activity, topography, and vegetation characteristics (Gerlach and Jasumback 1989, Rempel et al. 1995, Moen et al. 1996, Rumble and Lindzey 1997). Delusion of precision (DOP), a measure of the quality of satellite geometry with smaller values indicating lower triangulation error, can also affect the ability of the GPS collar to obtain a location. Blocking the satellites can: 1) cause positional delusion of precision to exceed the threshold of three to five, resulting in a 2-dimensional (2D) location; 2) reduce visible satellites to three, resulting in a 2D location; or 3) reduce the number of visible satellites to under three, making location impossible. If four satellites are visible to the GPS receiver, then latitude, longitude, and elevation can be calculated resulting in a 3-dimensional (3D) location, which, if differentially corrected, can be within 10 m of the true location (Wells et al. 1986). If three satellites are visible to the GPS receiver, the elevation value obtained from the last 3D position is substituted to solve the equations resulting in a 2D location. The error of this 2D location is directly related to the vertical distance that an animal has moved since its last 3D location, which, in areas of high relief, could be significant. Finally, when less than three satellites are visible, no location can be obtained.

Visibility of satellites in various vegetation or topographic types and the tendency of secretive animals to use areas of dense canopy cover may influence the accuracy of GPS locations and whether the locations are representative of the proportion of time an animal spends within a habitat.

Inferences of animal habitat selection directly drawn from GPS telemetry data are biased toward areas of open canopy (Rempel et al. 1995, Moen et al. 1996). However, if the magnitude and character of this bias can be determined, GPS telemetry can be critically evaluated against conventional telemetry techniques for studies of animal movements and habitats. In addition, biologists can then evaluate data relative to biases and possibly correct for some biases in GPS locations by employing techniques similar to those used in animal sightability models (Samuel et al. 1987, Steinhorst and Samuel 1989).

The effects of forest vegetation and topographic relief on obtaining accurate and representative locations of GPS receivers are unclear. GPS telemetry collars for large ungulates are expensive, thus, the benefit of using these collars depends on obtaining many accurate locations of animals. When describing habitat data, particularly at the microsite level, we believe 3D locations are the most useful. We examined the effects of forest structure and topography on obtaining 3D locations from GPS large-mammal radio collars in the Black Hills of Wyoming and South Dakota.

The objectives of this study were to quantify the effects of forest vegetation and topography on 3D locations obtained from GPS elk collars, and, if possible, to model the effects to correct bias associated with open canopy. A preliminary evaluation suggested that it might be possible to model bias of GPS locations in open canopy areas (Rumble and Lindzey 1997). The hypotheses we tested were: 1) forest vegetation characteristics will not affect the number of 3D locations obtained by GPS collars; and 2) topography will not affect the number of 3D locations obtained from GPS collars.

METHODS

Study Area

The study area is in the Black Hills National Forest (BHNF). Annual precipitation ranges from an average of approximately 46 cm to 66 cm (Orr 1959). Most precipitation occurs between April and July. January is typically the coldest month with mean temperature extremes of -11°C to 18°C. July and August are the warmest months with mean temperature extremes of 15°C to 29°C (Miller 1986). Elevations range from approximately 915 m to 2,207 m. Ponderosa pine *(Pinus ponderosa)* occurs throughout the Black Hills and is a dominant tree species. Other important tree species include white spruce *(Picea glauca)* occurring on north facing slopes, wetter sites, and at higher elevations, and quaking aspen *(Populus tremuloides)* (Hoffman and Alexander 1987).

Field Methods

We used three GPS radio telemetry collars (Version 2.10; Lotek Engineering, Inc.) designed for application on elk (*Cervus elaphus*). Each GPS unit was placed 2 m from the nearest tree on a tripod 0.5 m above the ground to approximate the height of a GPS collar on a bedded elk. Each individual GPS unit was programmed to collect locations at 30-min intervals and was placed at its location for approximately 24 h. If all satellites were operational, the current constellation of satellites guaranteed that six satellites were always visible (User's Manual 1994, Lotek Engineering, Inc., Newmarket, Ontario, Canada). Thus, 100% coverage in open environments was expected. Each GPS unit searched for satellites for up to 90 s; the first 25 s were spent searching for four satellites (3D location). If four satellites were not visible, the GPS unit searched for three satellites (2D location) for the remaining time with one caveat: a portion of the time remaining from locations obtained in <90 s was available to search >90 s for satellites on subsequent locations.

We stratified ponderosa pine, white spruce, and quaking aspen vegetation types into structural stages that included sapling-pole (2.5 cm to 25 cm diameter at breast height [DBH]) and mature timber (>25 cm DBH) with three overstory cover categories (OCC) of 0-40%, 41-70%, and >71% in each DBH category (Buttery and Gillam 1983). In each of these structural stages, we stratified slope into three categories of 0-30%, 31-60%, and >60%. In aspen stands, we tested GPS collars at the same location during summer when leaves were present and during winter when leaves were absent. We used Geological Information System (GIS) coverage of forest vegetation in the BHNF and digitized elevation models to find prospective stands of each vegetation structural stage-slope category. We verified the vegetation structural stage-slope category of each stand before placing the GPS collars for testing. We also placed a GPS collar in a meadow with no overstory component and negligible slope for comparison of forest locations to a benchmark location.

At each site, we characterized vegetation and topographic features. Measurements included OCC, percent slope, basal area (BA), DBH, average tree height, and average percent of the visible horizon. OCC was visually estimated with a spherical densiometer (Griffing 1985) positioned directly over the GPS collar. We used a l0-factor prism to determine trees >15.2 cm DBH to be measured in a variable radius circular plot. Trees ≤ 15.2cm DBH were measured in a 4.9 m-radius fixed plot. We recorded the DBH of all trees using tree calipers. Stand density index (SDI), a useful, relative measure of tree density, was calculated using the equation in McTague and Patton (1989) using average tree DBH, tree density, and BA. We also calculated an index of DBH x tree density for each site. We measured percent slope as the uphill reading of a clinometer for the first

50 m from the GPS unit at a height of 1 m. The angle of the visible horizon (lowest angle that sky was visible) was measured using a clinometer at 45° increments (n=8). The average of these angles was subtracted from 180 . The difference was then divided by 180 to estimate the percentage of visible horizon at each site.

Data Analysis

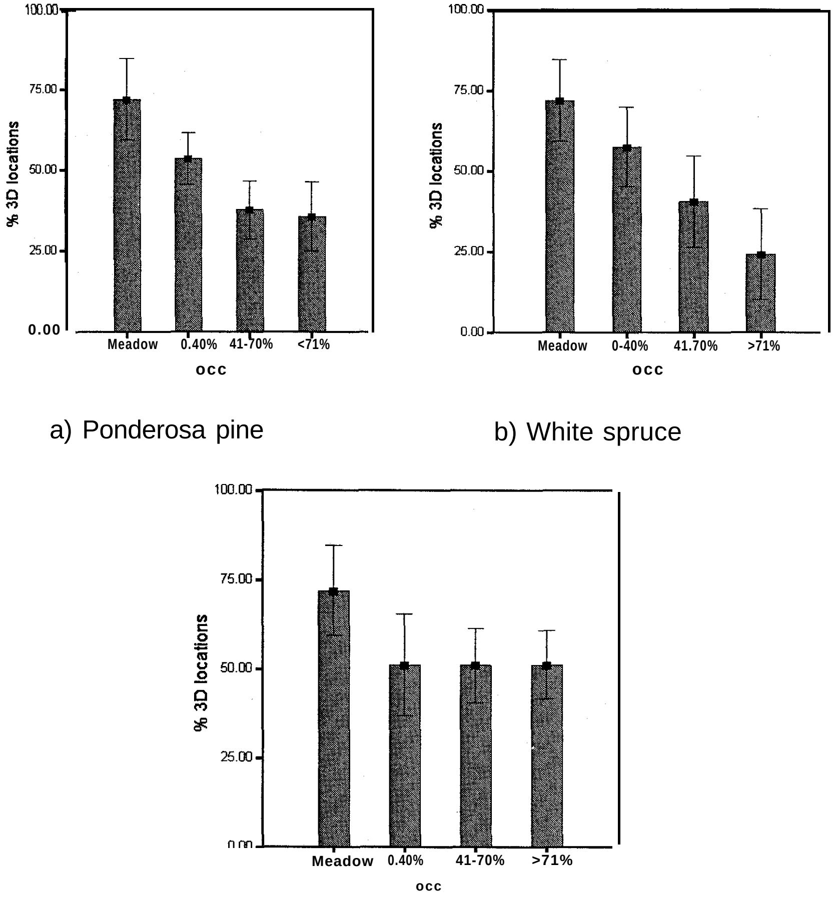
The hypothesis of no effect of vegetation on percent 3D locations was tested using 2-way analysis of variance between DBH categories and among OCC categories. There were no differences ($P > 0.3$) between DBH categories of ponderosa pine, white spruce, or aspen without leaves. Therefore, we pooled data for DBH categories and tested for differences among OCC categories using one-way analysis of variance for each forest type. We used Tukey's multiple range test if Levene's test (Milliken and Johnson 1984) for homogeneity of variance was non-significant and Dunnett's T-3 test (Dunnett 1980) if Levene's test was significant for post hoc comparisons of DBH categories.

Within each vegetation type, we used linear regression to model the average percent 3D locations with OCC, percent slope, timber density, DBH, tree height, DBH x tree density index, SDI, and percent of visible horizon. Multiple linear regression was used to model the percent of 3D locations using the better predictors obtained from linear regression. Variables were entered if they significantly (P = enter ≤ 0.1) contributed to the model.

RESULTS

We measured 36 sites each in ponderosa pine and in quaking aspen without leaves. Due to malfunction in the GPS units, only 19 sites each were measured in spruce and quaking aspen with leaves. Two meadow sites were measured for a relative measure of optimum performance of GPS collars.

As predicted, meadow sites had the highest percent of 3D locations. The percent of 3D locations declined from the 0-40% OCC to 41-70% OCC and >71% in ponderosa pine and white spruce (Figures la, 1b). In ponderosa pine stands with 0-40%, OCC had more 3D locations than 41-70% OCC ($P < 0.03$) and >71% OCC ($P < 0.02$). White spruce stands 0-40% OCC had more ($P = 0.002$) 3D locations than stands > 71% OCC. Percent 3D locations in white spruce 41-70% OCC did not differ from O-40 or >71% OCC. Percent 3D locations were the same ($P > 0.99$) among OCC categories of quaking aspen without leaves (Figure 1c). Percent of 3D locations in sapling-pole size quaking aspen stands with leaves differed from mature (P < 0.09). Failure of one GPS collar prevented quantitative comparisons among vegetation structural stages of quaking aspen with leaves.



a) Ponderosa pine

b) White spruce

c) Aspen without leaves

Figure 1. Graphs a, b, and, c are resulting percentages of 3D locations in each OCC structural stage.

Single regression analyses showed a decrease in OCC as the best predictor (P = 0.01, adj. R^2 = 0.27) of percent of 3D GPS locations in ponderosa pine. In white spruce, OCC also was the most highly correlated variable (P < 0.01, adj. R^2 = 0.5) in predicting percent 3D GPS locations. Average percent of visible horizon was the most highly correlated (P < 0.01, adj. R^2 = 0.37) single variable in obtaining 3D locations in aspen sites without leaves. In aspen with leaves, no significant correlations between percent 3D GPS locations and vegetation or topography were found.

Multiple regression improved the amount of variation in percent 3D GPS locations that could be accounted for by vegetation and topography in ponderosa pine and aspen without leaves stands. Multiple regression added slope to OCC as the most highly correlated ($P < 0.01$, adj. $R^2 = 0.39$) variable in predicting 3D locations in ponderosa pine. Positively correlated average percent of visible horizon and negatively correlated DBH resulted in an improved ($P < 0.01$, adj. $R^2 = 0.40$) predictive model in aspen without leaves. Multiple regression analysis of white spruce resulted in no improvement on the single regression model. No significant multiple variable model could be derived for aspen with leaves ($P > 0.1$).

DISCUSSION

Dense vegetation decreases the probability of obtaining 3D locations from GPS collars. We found that dense vegetation and steeper topography decrease the ability of GPS collars to obtain locations. Tree boles are physical barriers that can block GPS signals from satellites (Rempel et al. 1995, Moen et al. 1996). We anticipated that the index of tree density X DBH would reflect the blockage of satellite signals by tree boles. However, this variable was not as highly correlated with percent 3D GPS fixes as OCC. Theoretically, satellite signals can penetrate the needles of conifers (Rempel et al. 1995). In white spruce and ponderosa pine >71% OCC, 25% and 35% of location attempts, respectively, were 3D fixes. Therefore, some GPS signals are penetrating the conifer needles in white spruce and ponderosa pine. However, because OCC had the highest correlation with percent 3D fixes, our data suggest that increased canopy cover of conifers reduces the visibility of satellites to the GPS receiver on the collar.

We expected that the increased canopy coverage due to leaves (in deciduous aspen) would reduce the percent of 3D GPS locations compared to leafless (or winter) stands. In seven of 19 of our aspen stands with leaves, the percent of 3D locations increased from the number of 3D locations obtained at the same site without leaves. However, we are unable to explain these increases in 3D locations when leaves were present.

In a preliminary study by Rumble and Lindzey (1997), percent 3D GPS fixes showed similar declines with increasing OCC categories of ponderosa pine. The collars we used included updated communications software from the unit used by Rumble and Lindzey (1997). This software enabled the GPS unit to track 8 satellites when searching for satellite links to calculate the position, which resulted in reducing the time needed to establish a communication link with the satellite. The shorter time used to establish communication with satellites should increase the chance of obtaining a 3D location since more opportunities become available to establish links with satellites.

Regression analyses showed that the structural components of forest stands, particularly OCC, and the physical features of the landscape, such as percent available horizon or slope, can partially block or reduce the view of satellites from GPS collars. However, none of the OCC levels completely blocked all signals as evidenced by 3D locations obtained at all sites. The satellites used to acquire fixes are not geostatic; they orbit around the earth. Therefore, satellites are sometimes in a good configuration to obtain a 3D fix, while minutes or hours later they are in a configuration that only allows for a 2D fix. Furthermore, when compared to meadow sites that obtained about 72% 3D locations, the success of obtaining 3D locations in forest stands was good.

Either 2D or 3D locations are adequate for studies that describe general movements and home ranges. However, delineation of habitats used by animals within a home range is best addressed with the accuracy obtained with 3D locations. Researchers will need to account for bias in GPS locations due to vegetation and topography by testing the performance of GPS collars in forest vegetation and slope categories in their study area. Because GPS technology is changing, tests must be completed for each software or component upgrade before collars are placed on animals.

GPS technology in radio telemetry collars enables researchers to determine animal locations systematically at night, during poor weather conditions, or during other situations that are impractical for using conventional telemetry methods. Animal locations will be biased toward open habitats, but that bias can be considered and the tradeoffs of obtaining data from animals in remote areas, at night, or during winter storms must be evaluated. Continued advances in equipment will lead to further improvements in collar performance. At this time it would be inappropriate to extend these data to other forest types, topography, or GPS collars.

ACKNOWLEDGMENTS

The study plan for this research was designated as Forest Service RC-927. Financial support for this study was provided by the United States Department of Agriculture Forest Service, Rocky Mountain Research

Station, Black Hills National Forest, and the Wyoming Game and Fish Department.

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Biotelemetry 15

Proceedings of the 15th International Symposium on Biotelemetry

Juneau, Alaska USA, May 9-14, 1999

Edited by

John H. Eiler, Doris J. Alcorn,
and Michael R. Neuman

2000

International Society on Biotelemetry
Wageningen, The Netherlands

Symposium Hosted by

National Marine Fisheries Service, Auke Bay Laboratory
11305 Glacier Highway, Juneau, Alaska 99801 USA

773 pp