

Scott L. Findholt, Oregon Department of Fish and Wildlife, 1401 Gekeler Lane, La Grande, Oregon 97850

Bruce K. Johnson, Oregon Department of Fish and Wildlife, 1401 Gekeler Lane, La Grande, Oregon 97850

Larry D. Bryant,<sup>1</sup> USDA, Forest Service, Pacific Northwest Research Station, 1401 Gekeler Lane, La Grande, Oregon 97850, and

Jack W. Thomas,<sup>1</sup> USDA, Forest Service, Pacific Northwest Research Station, 1401 Gekeler Lane, La Grande, Oregon 97850

## Corrections for Position Bias of a LORAN-C Radio-Telemetry System Using DGPS

### Abstract

Position estimates determined from Long Range Navigation-C (LORAN-C) can be biased because of rugged topography, power lines, and mineral deposits. We corrected position bias of a LORAN-C automated animal tracking system used on the Starkey Experimental Forest and Range in northeast Oregon to track movements of Rocky Mountain elk (*Cervus elaphus nelsoni*), mule deer (*Odocoileus hemionus*), and cattle (*Bos taurus*). LORAN-C time differences were obtained from 386 Differential Global Positioning System sites located systematically throughout the Starkey Experimental Forest and Range. We used geostatistics to interpolate position-dependent LORAN-C distortions in the Starkey Experimental Forest and Range to improve the absolute positioning accuracy of the automated animal tracking system. Time differences were obtained from LORAN-C collars placed at 20 random sites. Positions were calculated after correcting these time differences for bias. These positions were compared for accuracy against the same positions determined by a Differential Global Positioning System (accuracy level within 2-5 m, Trimble Navigation, Inc.). Positioning accuracy increased for the original automated animal tracking system ( $P < 0.05$ ) when two corrected time differences were used to obtain positions but not in the upgraded automated animal tracking system ( $P > 0.05$ ) when 3-4 corrected time differences were used to determine positions. However, uncorrected positions from the upgraded automated animal tracking system were as accurate as corrected positions from the original automated animal tracking system. We are 90% confident that each LORAN-C position, after correcting for bias, was within a 3.4 ha area in the original automated animal tracking system and a 3.1 ha area in the upgraded automated animal tracking system, respectively. We believe that this attained level of accuracy will be adequate for habitat studies given the size distribution of habitat polygons within the Starkey Experimental Forest and Range. Methods presented to identify and correct bias of radio-telemetry positions can also be used to increase positioning accuracy of non-LORAN-C based radio-telemetry.

### Introduction

The potential of Long Range Navigation-C (LORAN-C) for wildlife research along coastal environments has been described (Patric et al. 1988, Boer et al. 1989, Collazo and Epperly 1995). Although Leptich et al. (1994) evaluated the accuracy of aircraft-based LORAN-C for wildlife research, few data are available on the terrestrial-based accuracy of LORAN-C, especially at sites in interior North America, and its usefulness for radio-tracking free-ranging wildlife.

In 1989, the automated animal tracking system was deployed on the Starkey Experimental Forest and Range (Starkey) to track positions of Rocky Mountain elk (*Cervus elaphus nelsoni*), mule deer (*Odocoileus hemionus*), and cattle (*Bos taurus*; Bryant et al. 1991, Johnson et al. 1991).

<sup>1</sup>Present address: USDA, Forest Service, 14th & Independence SW, P.O. Box 96090, Washington, DC 20090

This system computes positions of animals equipped with LORAN-C collars by differentially correcting the time differences of signals received by the collar and retransmitting them to the automated animal tracking system center (Dana et al. 1989). During summer and fall 1991, we placed LORAN-C receivers used to track animals at known positions computed by Differential Global Positioning System (DGPS) to determine the accuracy of the automated animal tracking system. Results of these tests showed multi-directional biases in LORAN-C positions up to 150 meters, particularly in the northwest corner of the study area (S. L. Findholt, unpubl. data). A bias of this magnitude was considered unacceptable given the distribution and size of habitat patches within Starkey and the goals of our research. Therefore, our objectives were to: (1) report on the accuracy of a terrestrial-based LORAN-C radio-telemetry system at an interior study site, (2)

document the magnitude and extent of LORAN-C biases within Starkey, (3) develop corrections to increase position accuracy of the automated animal tracking system, and (4) evaluate the extent to which corrections improved accuracy. In this paper we used White and Garrott's (1990) definition of bias which is a mean error significantly different from zero.

## Methods

### Description of Study Area

The study area included most of the Starkey Experimental Forest and Range, located on the Wallowa-Whitman National Forest, about 35 km southwest of La Grande, Union County, Oregon (Figure 1). Vegetation on Starkey is a mosaic of forest stands and open areas (Strickler 1965). Forest stands are dominated by ponderosa pine (*Pinus ponderosa*), with grand fir (*Abies grandis*) and Douglas fir (*Pseudotsuga menziesii*) occurring on northern aspects. Soils are derived from basalt and pumicite (Strickler 1965). The 10,102 ha study area at Starkey is enclosed with a 2.4 m high fence that restricts movements of elk and deer. Elevation ranges from 1,120 to 1,500 m.

### Magnitude and Extent of LORAN-C Bias

We used the University of Calgary's LORCAL system to determine the magnitude and extent of position-dependent biases within Starkey (Lachapelle and Townsend 1991). LORCAL is a portable system used for the signal analysis and calibration of LORAN-C using DGPS. From 25 November to 27 November 1991, approximately 20,000 data points were collected covering nearly 242 km of accessible roads within Starkey.

### Differences Between Original and Upgraded Automated Animal Tracking System

Dana et al. (1989) described the original automated animal tracking system installed at Starkey. Briefly, the base station computer requests a position from the radio collar via a coded signal that activates the collar's LORAN-C receiver. LORAN-C signals received by the collar are rebroadcast by the collar over a microwave link to radio towers that relay the signals to the base station. Positioning software converts the LORAN-C signals into differentially corrected UTM coordinates and stores the results in the computer. In the original

radio-telemetry system at Starkey positions were computed every 15 seconds, whereas in the upgraded system, positions are obtained every 20 seconds.

The main differences between the original and upgraded radio-telemetry systems affecting position accuracy are the number and locations of LORAN-C transmitters used by each system (Figure 1). In the original automated animal tracking system, positions were determined from three LORAN-C transmitters from the U.S. West Coast chain (Group Repetition Interval, GRI 9940) located at George, Washington (9940W), Fallon, Nevada (9940M), and Middletown, California (9940X). The upgraded system, installed on 17 July 1992, uses six LORAN-C transmitters, the original three along with three others: Searchlight, Nevada (9940Y) and transmitting towers at Havre, Montana (8290M) and Williams Lake, British Columbia (8290Y) from the North Central U.S. (NOCUS) LORAN-C chain (GRI 8290).

### Corrections for LORAN-C Bias

Corrections for bias were developed for the original and upgraded automated animal tracking systems. From 24 February 1992 to 15 May 1992, a systematic sample of 372 sites was located within Starkey at approximately 400 m intervals. At each site, LORAN-C time differences were measured on 9940W and 9940X using a portable, land-based Apollo Model 602 LORAN-C receiver (II MORROW Inc., Salem, OR). After learning that the upgraded automated animal tracking system at Starkey would use data from GRI 8290 and a fourth transmitter from GRI 9940, time differences were measured at 14 random sites located throughout Starkey for 9940Y and 8290Y. Time differences obtained with the remote LORAN-C receiver were differentially corrected with data from an Internav LC408 dual-chain LORAN-C receiver at the Starkey computer center. Without differential correction, LORAN-C position error would increase by about 1,200 m at Starkey. LORAN-C time differences were measured to the nearest 0.1 micro-second ( $\mu$ s; i.e., 30 m).

A true position was determined for each of 386 sites at Starkey by collecting a minimum of 180 three-dimensional fixes at each site with a GPS receiver (Trimble Pathfinder, Trimble Navigation Ltd., Sunnyvale, CA). DGPS operating parameters used were an elevation mask of 15



Figure 1. Locations of LORAN-C transmitting towers in the western United States and Canada used to obtain position estimates on the Starkey Experimental Forest and Range, northeast Oregon. LORAN-C transmitting towers at Fallon (Nevada), Middletown (California) and George (Washington) were used in the original automated animal tracking system. These transmitting towers in configuration with those at Williams Lake (British Columbia), Havre (Montana), and Searchlight (Nevada) were used in the upgraded automated animal tracking system.

degrees, a signal-to-noise ratio mask of 6, position dilution of precision (PDOP) mask of 8, and PDOP switch of 6. The 180 positions were differentially corrected using data from the Pacific Northwest Region Community Base Station in Portland, OR, 319 km from the computer center at Starkey, and then averaged for a single position for each site. Base station positions were collected at 5-second intervals with a GPS receiver (Newton 6 channel, Trimble Navigation Ltd., Sunnyvale, CA). DGPS estimated positions were compared to three sites within Starkey with known locations to assess the accuracy of DGPS. UTM coordinates obtained by DGPS were converted to the appropriate time differences for each pair of LORAN-C transmitters. The differences between the differentially corrected LORAN-C and DGPS time differences represent the distortion in the LORAN-C signals. We used the North American Datum of 1983 for both LORAN-C and DGPS geographic locations.

#### Evaluating Success of Correcting Position Bias

First, we tested 40 radio-telemetry collars at a DGPS site within Starkey and determined that all collars were functional and provided the same positions. Then two collars were placed approximately 1.5 m above ground at each of 20 random sites within Starkey. A random sample of approximately 300 attempted positions was obtained from each collar, 24-hr each day from 27 October 1992 to 3 November 1992. Each time difference was screened for minimum threshold values of signal strength and signal-to-noise ratios. Two time differences (3-4 time differences in the upgraded automated animal tracking system) that met minimum criteria were used to calculate a UTM coordinate position. The number of usable positions for the analysis varied from 34 to 240 for each collar. For each position, predicted time difference corrections, calculated from block kriging algorithms, was added to or subtracted from each time difference obtained and the corrected position was determined. To evaluate how successfully we corrected bias from our LORAN-C positions we compared UTM coordinates obtained from DGPS at each site with both uncorrected and bias-corrected LORAN-C position estimates for both the original and upgraded automated animal tracking systems. A single measure of error was calculated as the hypotenuse of a right triangle

whose legs were the difference between the estimated DGPS and LORAN-C UTM coordinates.

#### Area Estimates of Radio-telemetry Positions

The same data set that was used to evaluate our success at correcting LORAN-C position bias was used to calculate the area estimates of radio-telemetry positions. Area estimates were based on the distribution of radio-telemetry positions surrounding point estimates at each of the 20 DGPS radio collar sites.

#### Statistical Analyses

Because bias of LORAN-C positions was spatially autocorrelated, we used geostatistics to interpolate time difference distortions throughout Starkey for LORAN-C transmitters 9940X, 9940Y, 9940W, and 8290Y (Gamma Design Software 1992). We evaluated the degree of autocorrelation among measured data points using semi-variance statistics (Marx and Thompson 1987, Robertson 1987). Isotropic semivariogram models of time difference distortions were obtained with weighted least squares analysis and used to interpolate values for points not measured using block kriging algorithms. We used a jackknife analysis to compare estimated values for each sampled coordinate with actual values.

We used block kriging to estimate time difference distortions for 500 m<sup>2</sup> areas within Starkey for GRI 9940X and 9940Y and 2000 m<sup>2</sup> areas for GRI 9940Y and GRI 8290Y. We estimated time difference distortions for each block with weighted values of 12 nearest measured time differences within a 3,000 m search radius of the block. Points within the block contributed relatively more to time difference distortions than points outside the block.

We used a completely randomized block ANOVA to compare bias of uncorrected data with data corrected for bias (results from block kriging algorithms only) for both the original and upgraded radio-telemetry systems. We used a Student-Newman-Keuls multiple comparison range test to determine whether corrected or uncorrected positions contained less bias.

### Results

#### Magnitude and Extent of LORAN-C Bias

Results from the LORCAL system indicated that biases in LORAN-C positions ranged from 0 to

200 meters in absolute magnitude. The largest biases were found in the northwest corner of the study area.

### Success at Eliminating Bias From LORAN-C Radio-telemetry Positions

Summary statistics of isotropic semivariograms for time difference distortions used to evaluate topography-induced bias are presented in Table 1. All correlation coefficients were significant at

$P < 0.05$ . The results of jackknife analysis indicated that estimates of points were highly correlated for observed time differences ( $P < 0.01$ ).

Position bias varied ( $F = 7.79$ ; 3,57 df;  $P = 0.0002$ ) among groups (Figure 2). We were able to significantly improve accuracy ( $P < 0.05$ ) of the original automated animal tracking system when positions were corrected for bias. The mean difference between corrected and uncorrected positions for the initial automated animal track-

TABLE 1. Summary statistics of semivariograms of LORAN-C time difference distortions measured in  $\mu\text{s}$  and used to estimate positioning bias of an automated animal tracking system throughout the Starkey Experimental Forest and Range, northeast Oregon.

LORAN-C transmitter	<i>n</i>	Model	Co <sup>a</sup>	Co+C <sup>b</sup>	Ao <sup>c</sup>	<i>r</i> <sup>2</sup>	<i>P</i>
Middleton (9940X)	372	Linear/sill	0.001	0.021	6650	0.978	<0.0001
George (9940W)	372	Exponential	0.0025	0.0168	839	0.901	<0.0001
Searchlight (9940Y)	14	Exponential	0.00001	0.00711	2840	0.666	<0.05
Williams Lake (8290Y)	14	Spherical	0.000210	0.0452	12600	0.837	<0.05

<sup>a</sup>Nugget variance.

<sup>b</sup>Sill (structural variance plus nugget variance).

<sup>c</sup>Range of autocorrelated data, in meters.

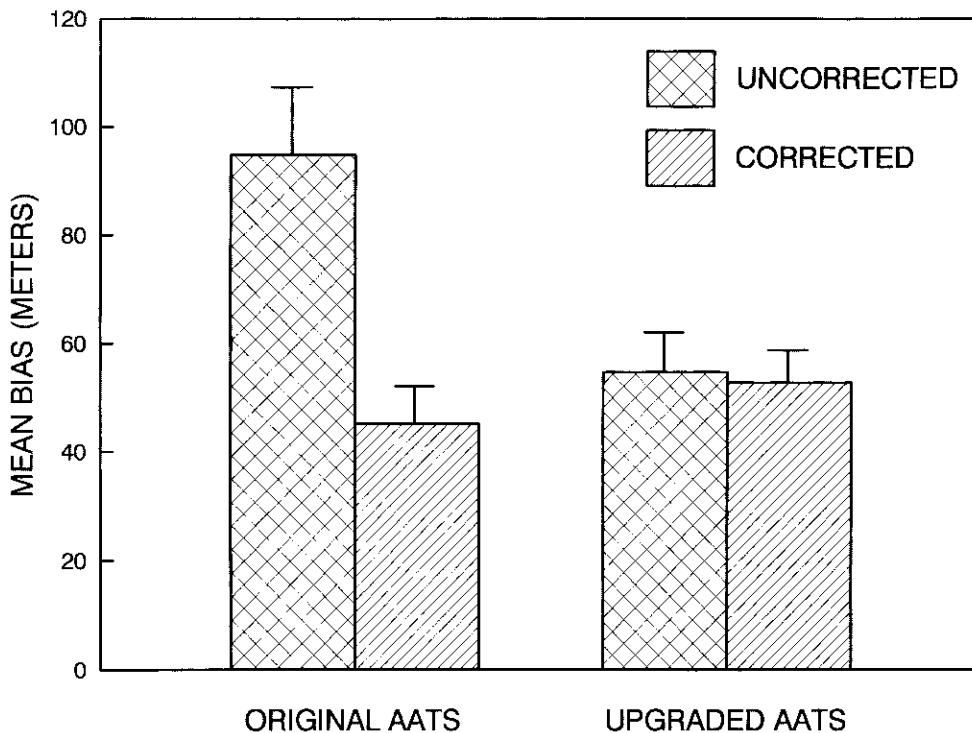


Figure 2. Mean bias and standard error of LORAN-C position estimates ( $n = 20$  sites) from the original and upgraded automated animal tracking systems (AATS) used on the Starkey Experimental Forest and Range, northeast Oregon.

ing system was 49.6 m, and at 15 of 20 sites, differences between LORAN-C and DGPS positions were reduced (Figure 2). There was a marked improvement in accuracy of telemetry positions (corrected and uncorrected) in the upgraded automated animal tracking system compared to the original automated animal tracking system because bias was significantly reduced when positions were determined from 3-4 time differences instead of two time differences and because of better configuration of NOCUS chain LORAN-C transmitters in relation to Starkey. Accuracy of positions from the upgraded automated animal tracking system, however, was not significantly improved after corrections were made for bias ( $P > 0.05$ ). Bias was however, reduced at eight of 20 sites.

Mean error of DGPS used at known geodetic reference sites within Starkey was 3.4 m (SE = 0.612,  $n = 3$ ). Using corrections to remove bias from telemetry positions, the area estimate of each position from the original and upgraded automated animal tracking system was 3.4 ha and 3.1 ha (90% C.I.), respectively. The probability that each position is near the center of the area estimate is much greater than near the perimeter.

## Discussion

Time- and position-dependent factors influence LORAN-C performance on land. Time-dependent errors, i.e., atmospheric conditions, can be partially removed using differentially-corrected LORAN-C. This technique involves placing a LORAN-C receiver at a base station with a known location. LORAN-C signal variations are measured at the known location and differential corrections are calculated for each remote station time difference measurement. This method is most effective when the distance from base station to remote is small and the terrain is flat.

Differential LORAN-C is less effective for correcting position-dependent biases, especially over rugged terrain (Lachapelle and Townsend 1991). However, proper calibration of a LORAN-C receiver at known positions established with DGPS can be effective at reducing position bias.

We assumed that the source of LORAN-C position biases were mostly the effect of terrain within Starkey. According to Lachapelle and Townsend (1991), the effect of rugged topography on LORAN-C can result in local position biases

up to several hundred meters. In addition, these distortions can vary by a few hundred meters per km. Position-dependent bias in LORAN-C can also be caused by power lines and mineral deposits (II Morrow Inc., 1990). Power lines are absent within most Starkey. It seems unlikely that the magnitude of position bias observed at Starkey could have been caused by mineral deposits (Lachapelle and Townsend 1991).

A marked reduction in position bias of final telemetry positions was evident in the upgraded automated animal tracking system compared to the original system. LORAN-C accuracy depends mostly on distance from transmitting stations, the geometry between transmitters, and type of terrain (Boer et al. 1989, White and Garrott 1990). The geometry of the LORAN-C transmitting towers was improved with the addition of two transmitting towers from the NOCUS chain. Also, bias may have been significantly reduced when positions were determined from 3-4 time differences instead of two time differences.

Time difference corrections from geostatistical analysis improved the accuracy of the original automated animal tracking system on Starkey. However, corrections did not remove all the position bias in the original automated animal tracking system. Lachapelle and Townsend (1991) found that LORAN-C biases of 50-100 m represented the limits of accuracy that could be achieved for the calibration of LORAN-C with DGPS. Those researchers also indicated that it was not possible to separate completely the position-dependent conductivity due to ground moisture and terrain effects from the atmospheric and other time-dependent effects. Corrected position bias at Starkey was well within the limits of attainable accuracy of LORAN-C reported by Lachapelle and Townsend (1991).

Corrections from geostatistical analysis for the upgraded automated animal tracking system did not significantly reduce bias. One possibility for the lack of bias reduction is because of our LORAN-C equipment signal-travel-time measuring accuracy (0.1  $\mu$ s or 30 m), thus reducing our ability to develop more accurate corrections. Also, we measured LORAN-C time differences for 9940Y and 8290Y at 14 DGPS sites which may have been an inadequate sample size given the variability in LORAN-C distortions found with the other two time differences (9940W and 9940X).

We did not pursue reducing bias in the upgraded automated animal tracking system further because it was not significantly different from position bias associated with the original automated animal tracking system after bias corrections were made.

The mean position error of the land-based automated animal tracking system at Starkey of 45.3 m (SE = 7.07) and 52.8 m (SE = 5.87) for the original and upgraded automated animal tracking system, respectively was much better than that reported for other LORAN-C study areas. The mean position error for a stationary, ground based LORAN-C on the Rhode Island coast was 97 m (Patric et al. 1988). Collazo and Epperly (1995) reported a mean position error from 64 to 99 m from a land-based LORAN-C in an estuarine habitat in Core Sound, North Carolina. Leptich et al. (1994) found a mean position error of approximately 200 m for an aircraft-based LORAN-C in northern Idaho.

Radio-telemetry provides a useful technique for studying habitat use and selection by wildlife. However, habitat studies require accurate estimates of an animal's location so that it can be correctly placed in a habitat type (White and Garrott 1986, 1990; Nams 1989). Accurate estimates are especially important when the study area contains a mosaic of small habitat patches because large area estimates may include two or more habitat types. Although both aerial and triangulation radio-telemetry methods often result in errors, these errors are generally ignored when determining environmental characteristics of estimated positions (Saltz 1994). The effect of error in the estimates of positions is to lower the power of tests of habitat selection (White and Garrott 1986).

Mean patch size of the 15 plant community types determined from aerial photo interpretation within Starkey was 14.6 ha ( $n=613$ , SE = 4.46; S.L. Findholt, unpubl. data). Size distribution of

habitat polygons is skewed toward smaller sizes. Using corrections to remove bias from radio-telemetry positions, the area estimate of the original and upgraded automated animal tracking systems was 3.4 ha and 3.1 ha (90% C.I.), respectively. The accuracy of LORAN-C radio-telemetry positions appears to be adequate for habitat studies being conducted on elk, deer and cattle within Starkey after bias is removed from the position data.

We believe that the methods described in this paper to reduce radio-telemetry position bias can increase the accuracy of LORAN-C collar radio-telemetry; this should result in greater power of statistical tests of habitat selection. In addition, the techniques used to quantify and correct bias from LORAN-C positions at Starkey can also be used to improve the positioning accuracy of non-LORAN-C based radio-telemetry.

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