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EVALUATING GPS COLLAR ERROR: A CRITICAL EVALUATION OF TELEVILT POSREC-SCIENCE™ COLLARS AND A METHOD FOR SCREENING LOCATION DATA

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Wildlife telemetry collars incorporating Global Positioning System (GPS) units are thought to provide accurate locations when the GPS receiver obtains an adequate sky view. We deployed 32 POSREC-Science™ 600 series 12-channel GPS collars (Televilt/TVP Positioning AB, Lindesberg, Sweden) on mule deer, *Odocoileus hemionus*, and bighorn sheep, *Ovis canadensis*, in three California

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mountain ranges from 2002 to 2005. Evaluation of data from those deployments showed numerous implausible movements, which lead us to question the accuracy of POSREC GPS collars. Because of the questionable data encountered, we tested the precision of Televilt POSREC-Science™ 600 collars under several conditions: 1) an area of optimal sky visibility; 2) *ad hoc* test locations where collars remained attached to deceased mule deer prior to recovery of the collar; and 3) *ad hoc* test locations inside a 1-floor, wood-framed building, or outside the homes of two biologists, for a total of 663 GPS positions. Unprecedented errors in excess of 2 km occurred in 2% of fixes, whereas 12% of fixes were >1 km and 53% > 100 m from the true location. Comparisons among six additional GPS collar models from three manufacturers showed POSREC collars to be unique in their lack of precision. Because viewing point data alone may belie the presence of flawed GPS fixes, we urge researchers using GPS collars, particularly Televilt POSREC collars, to evaluate patterns of movement to ensure that data are not affected by sampling artifacts. We developed a method for screening GPS collar data and provide an ArcView extension useful for removing erroneous fixes. We suggest researchers contemplating purchases of GPS collars obtain test data from the individual collars they will deploy, to ensure that real-world precision meets study objectives.

INTRODUCTION

Studies of GPS accuracy have evaluated effects of canopy and terrain (Rempel et al. 1995, Dussault et al. 1999, D'Eon et al. 2002, Di Orio et al. 2003, Cain et al. 2005, DeCesare et al. 2005) as well as collar orientation (Moen et al. 1996, D'Eon and Delparte 2005). These studies elucidated external influences on location accuracy, and have important implications for the interpretation of data from GPS collars (D'Eon 2003, Frair et al. 2004). These comparisons of accuracy in commercially available GPS collars, however, have been limited to collars made by Advanced Telemetry Systems (ATS; Isanti, Minnesota), Lotek Wireless (Newmarket, Ontario), and Telonics, Inc. (Mesa, Arizona). Frair et al. (2004) and Gau et al. (2004) provided data on respective fix rates and reliability of Televilt GPS-Simplex™ collars, but did not assess accuracy or precision. This work documents the unprecedented magnitude of location errors inherent in widely deployed Televilt POSREC-Science™ GPS collars.

Evaluation of GPS collar error was not a planned objective of our studies, but when extraordinarily improbable position data were detected after deploying collars on study animals, we sought data from collars at fixed locations to verify the presence of errors. To this end, we combined controlled testing with opportunistic data from fixed locations identified retrospectively from a database of GPS collar fixes, yielding data from several GPS collar models under a range of satellite visibility conditions and illuminating the prevalence of heretofore unprecedented errors. We also provide a method that is broadly applicable to screening GPS collar data for patterns characteristic of flawed locations.

METHODS

Our methodology emanated in response to conspicuous problems with data obtained from deployment of POSREC GPS collars and our need to quantify apparent location errors. Data were compiled from a variety of sources including planned tests, pre-deployment testing, opportunistic data collected from collars deployed in the field that became stationary after collar loss or animal mortality, and from collars tested during past research. Our methods were not intended to generate data suitable for side-by-side comparisons of accuracy among GPS collar models, but instead to present a representative range of location error from GPS collars, including those of three models from Televilt currently absent in the literature, for comparison with POSREC collars.

Field Deployment of POSREC Collars

We deployed POSREC 600-series store-on-board collars on mule deer (Krausman et al. 2004) beginning in March 2002 in Round Valley, California (37°25'N, 118°37'W), at the base of the Sierra Nevada, as part of long-term study of predator-prey interactions (Pierce et al. 2000, Pierce et al. 2004). Additional collars were similarly deployed on mule deer in the San Ysidro mountains, California (33°13'N, 116°30'W). Eleven collars were re-deployed during 2002-2005 when collars were recovered after animal mortality or after recapture and subsequent refurbishment of collars. Seven collars were re-deployed on bighorn sheep inhabiting the White Mountains (37°25'N, 118°14'W) and Sierra Nevada (36°32'N, 118°11'W) in 2004. Resultant field data included locations from a total of 50 animal deployments of 32 POSREC 600-series store-on-board GPS collars. All collars were programmed by the manufacturer to attempt GPS fixes at intervals of 1-6 hours. We shipped collars to the former distributor, Telemetry Solutions (Walnut Creek, California) or, after 5 May 2005, directly to Televilt for download, and data were returned as e-mail attachments. We imported data into ArcView 3.3 (Environmental Systems Research Institute, Redlands, California) and used the Animal Movement extension (Hooge and Eichenlaub 1997) to connect sequential GPS positions. Data were projected into UTM coordinates and retained the WGS 1984 datum. We overlaid movement paths on a shaded relief map generated from a digital elevation model (DEM) with 30 m resolution. Visual examination of locations was employed to identify suspect movements exhibiting an acutely angled out-and-back pattern (Fig. 1).

Fixed-Location Testing of GPS Collar Precision

Data from fixed locations were assembled from a combination of planned test sites, *ad hoc* tests where drop-off mechanisms released collars from study animals or where animals died, and *ad hoc* locations of collars activated before deployment or after recovery. We used the mean of 3-D fixes from collars as the reference location (Dussault et al. 2001) and calculated error distance from this centroid. In the absence

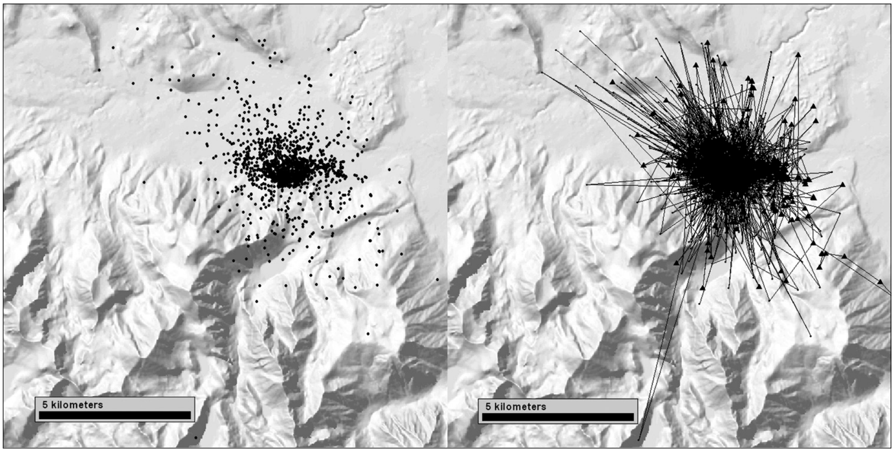

Figure 1. All point locations (left) and movement path (right) generated from POSREC GPS collar deployed on mule deer RVD210, 10 Apr 2002–21 Sep 2002; all fixes (2-D and 3-D; n=1895). "3-D" and "3-D+" fixes (n=1344) denoted by triangles.

of an independent measure of the true location, this is a measure of precision rather than accuracy *per se*. We did, however, test for bias using the average of 100 3-D locations collected with a Rockwell PLGR (Rockwell Collins, Cedar Rapids, Iowa.), Garmin GPS12XL, or GPS III (Garmin, Inc., Lenexa, Kanas.) receiver at each planned test location. Additional collar data were requested from Telemetry Solutions, at the time the distributor of Televilt products in the Americas.

We conducted tests of ATS 2000 model year (n=8) and Lotek GPS 2000 (n=7) collars in the vicinity of Seward, Alaska (60°06'N, 149°27'W) from 6 May 2000, (4 days after selective availability was disabled; Lawler 2000) through 11 August 2000, at a total of 22 planned test sites and 2 dropped-collar sites. Most planned sites (78%) were located under closed-canopy (e.g., *Alnus crispa* or *Picea sitchensis*), as were two dropped collars. Locations were distributed over a range of slopes and aspects. Collars were oriented upright at approximately 0.5 m height; however, 30% of test collars were disturbed by black bears, *Ursus americanus*, during the 1-20 day trials, resulting in horizontal or downward orientation of the GPS antenna. We pooled the 953 (ATS) and 939 (Lotek GPS 2000) GPS positions by manufacturer. These data represent a range of worst-case conditions of canopy cover, topography, and collar orientation in a steeply sloped, high-latitude environment.

One POSREC collar was tested in an area of optimal sky view at 1-m height in sagebrush, *Artemesia tridentata*, habitat in Bishop, California (37°22'N, 118°24'W) for 14 days. We augmented planned collar testing with retrospective analyses of instances where immobile GPS collars provided additional and unplanned data useful for determining the extent of location errors. Position data from fixed collars were obtained from POSREC collars that continued to acquire fixes while on deceased mule deer (n=2 collars) for 12 and 22 days prior to recovery. Data also were obtained from POSREC collars outside the homes of two biologists (n=2; 4 and 92 days), and from three collars active for 13-201 days on shelves inside a 1-floor wood-framed building

Table 1. Percentile[a] location errors (m) for eight GPS collar models and one handheld GPS unit with exceptional errors denoted by bold type.

GPS Model		Location	All 2-D and 3-D fixes					3-D fixes				
			n	50%	95%	99%	100%	n	50%	95%	99%	100%
ATS	Year 2000	Outdoor[b]	953	9.3	65.5	161.7	486.3	660	8.3	42.8	107.9	486.3
	G2000	Indoor[c]	66	10.5	82.2	___	167.3	28	7.8	33.4	___	37.2
Garmin	III Plus	Indoor[c]	100	8.0	39.0	171.5	172.7	82	7.4	36.1	___	55.5
Lotek	GPS2000	Outdoor[b]	939	11.1	64.4	240.8	338.4	388	10.1	41.1	240.7	338.4
	GPS4400s	Outdoor[d]	98	5.5	24.0	___	117.2	94	5.5	20.0	___	72.7
Televilt	Posrec	Indoor[c]	351	**470.4**	**1735.4**	**2565.5**	**3352.9**	117	15.2	**852.6**	**1429.9**	**1486.3**
	Posrec	Outdoor[e, f]	312	8.7	**951.9**	**1681.5**	**2139.5**	215	5.9	53.0	**904.7**	**1165.1**
	Simplex	Indoor[g]	868	8.3	36.8	81.4	317.4	291	8.1	20.8	28.1	34.1
	Simplex	Outdoor[d, f]	249	8.3	20.1	44.0	127.3	87	3.8	15.8	___	17.1
	Tellus	Indoor[g]	81	20.0	58.5	___	465.6	38	19.4	61.3	___	465.6
	Tellus	Outdoor[d, f]	208	12.1	68.6	138.5	260.6	195	12.5	67.6	142.1	260.6
	Prototype[h]	Outdoor	191	6.9	21.0	50.2	118.4	147	6.5	17.4	82.8	118.4

[a] Percentile errors are also referred to as CEP (circular error probable).
[b] Planned test locations (ATS, Lotek) and unplanned tests at dropped collar locations (n=385 of 939 fixes; Lotek), vicinity of Seward, Alaska.
[c] Interior of wood-framed building, Bishop, CA.
[d] Pre-deployment tests on truck dashboard, Bishop, CA.
[e] Planned test in optimal sky view area, Bishop, CA (n=101 fixes)
[f] Unplanned tests at deer mortality locations and outside the homes of biologists, vicinities Bishop and San Ysidro, CA.
[g] Pre-deployment test in windowsill, Bishop, CA.
[h] Data from POSREC prototype collar (see discussion).

in Bishop (hereafter “indoor" location), for a total of 663 positions collected under GPS receiving conditions ranging from optimal to marginal. Additional fixed-collar position data were collected from Lotek 4400s (n=2; 2 and 12 days), Televilt Simplex (n=3; 6-119 days), and Televilt Tellus (n=3; 5-14 days) collars in 2003-2006 under similar conditions (Table 1). In an effort to replicate conditions at the indoor location where most fixed-location POSREC GPS collar data were collected, we activated four ATS model GPS2000 GPS collars at the same interior location for 16 days. We further employed a Garmin III Plus handheld GPS receiver to collect fixes over a 24-day period (median frequency of fixes=48.5 min) to explore the possibility that this indoor location could cause a marked increase in GPS location error.

Error Screening

We explored metrics to identify suspect out-and-back movements among GPS collar data from animal deployments to separate pseudo-movements resulting from likely artifacts in the data from actual animal movements. We wrote scripts in ArcView to calculate angular deviation (Zar 1999), mean length and mean rate of sequential movement vectors (V_n,V_{n+1}), and the standard deviation of mean length and mean rate, relative to prior and subsequent movement vectors. We also used a DEM to derive slope and aspect for each GPS location. Movement vectors >500 m in length followed by vectors with azimuths of near 180 degree opposition were subjectively identified as “bad” when we judged the GPS fix improbable because of intervening topography, distance from other fixes, or unusually high speed of the implied movement. Movement vectors that appeared valid were subjectively identified as “good”. We used SPSS 11.0 for Mac OS X (SPSS Inc., Chicago, Illinois) to generate a logistic regression model of the probability a GPS position was flawed, based upon the characteristics we judged were likely to indicate an erroneous location (Hosmer and Lemeshow 2000). Logistic regression is applied as a tool to differentiate characteristics of uncontrolled data gathered from animal deployments, where the true locations and movements are unknowable. Forward stepwise selection was employed on variables derived from ArcView, with P=0.15 for entry and P=0.20 for removal. We developed an ArcView 3.x extension incorporating the metrics calculated above to generate a logistic probability for each position in an animal movement path.

RESULTS

Field Deployment of POSREC Collars

POSREC collar deployed on mule deer and bighorn sheep yielded a total of 89,283 positions, and produced star-shaped patterns when sequential fixes were connected (Fig. 1). Sequential vectors showed thousands of improbable out-and-back movements of up to 16 km (one-way), sometimes traversing 3,500 m mountains in winter, and returning to nearly the starting location ≤6 hours later. Elimination of 2-D fixes (n=24,097 or 27.0%) reduced the magnitude and frequency of suspect movements,

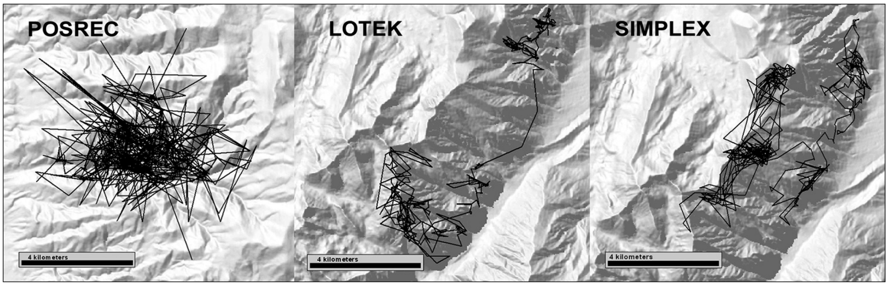

Figure 2. GPS collars deployed on a desert bighorn ewe D7 (POSREC; n=852 locations) and Sierra Nevada bighorn ewe S62 (Lotek GPS 4400s; n=1035 locations) and ram S18 (Televilt Simplex; n=651 locations) over the same period: 20 Mar – 8 Sep in 2004 (Posrec, Simplex) and 2005 (Lotek). All fixes (2-D and 3-D) are included.

but did not eliminate them (Fig. 1). These novel patterns were present in data from all POSREC collars (n=32) regardless of taxon or study area, though implausible fixes did not become apparent until sequential positions were connected. Once movement paths were generated, however, the star-shaped patterns were prominent and uncharacteristic of paths generated using other GPS collars (Fig. 2). POSREC collar data did not provide dilution of position (DOP) information that could have enabled the screening of fix quality (D'Eon and Delparte 2005). Neither did data include the number of satellites used to obtain a fix, though a fix category of "3-D+",

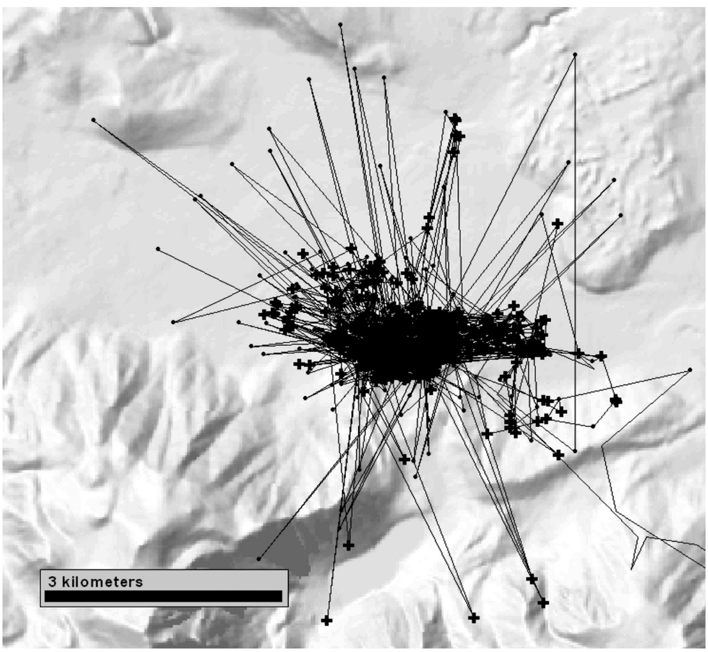

Figure 3. POSREC GPS collar movement path, mule deer RVD210, 10 Apr 2002–21 Sep 2002, generated from 3-D and better fixes (n=1344). Crosses denote "3-D+" fixes (n=840).

meaning that ≥5 satellites were used to solve for the position, is provided in addition to the conventional "2-D" and "3-D"[2]. These "3-D+" locations comprised 44.8% of GPS fixes from animal deployments, and displayed noticeably fewer anomalous fixes, though questionable locations remained (Fig. 3). A fourth category of "1-D" (n=1,246 or 1.4%) is what Televilt describes as a fix calculated with <3 satellites, using parameters from previous positions[2]. We eliminated 1-D locations from our analyses.

Fixed-Location Testing of GPS Collar Precision

No GPS collar showed directional bias relative to averaged 3-D positions with a Rockwell PLGR, Garmin GPS12XL, or GPS III at planned test locations. The 95% confidence interval for each collar overlapped those of the averaged handheld GPS receiver.

POSREC collars displayed errors greater than any other collar at ≥95th percentile,

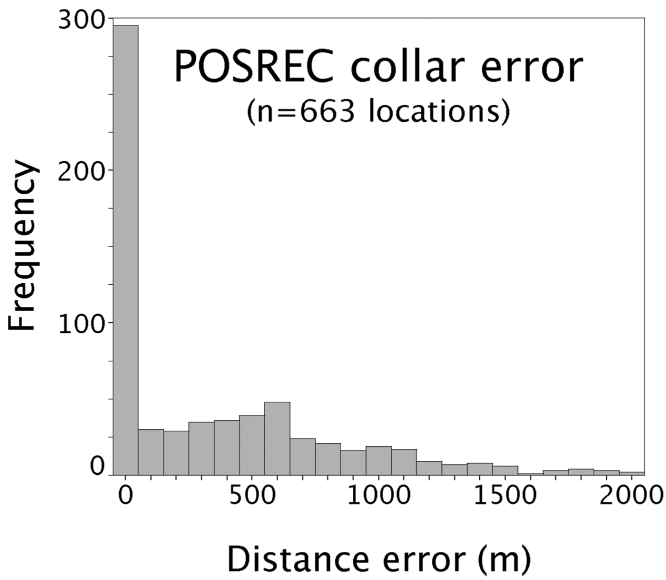

Figure 4. Error distribution (all 2-D and 3-D fixes) from fixed-location POSREC collars. Errors >2100 m (n=7) not illustrated.

with location errors for combined 2-D and 3-D locations that exceeded one order of magnitude larger than for every other collar tested (Table 1). These unique errors were characterized by a bimodal error distribution with the expected log-normal distribution for errors <100 m, and a second peak at approximately 600 m (Fig. 4). This unanticipated distribution persisted among 3-D fixes after elimination of 2-D

[2] Televilt/TVP Positioning AB, unpublished document, "What is fix type.txt"

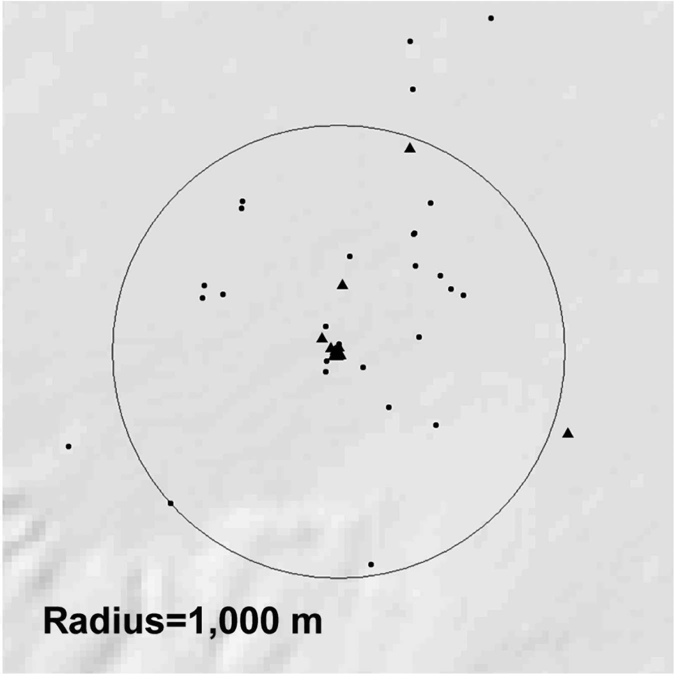

Figure 5. POSREC collar C600-175 tested under optimal sky visibility. N=101 fixes (2-D and 3-D). 3-D fixes (n=76) denoted by triangles.

positions. None of the 154 "3-D+" fixes, however, showed errors >135.8 m. The single POSREC collar tested under optimal sky-view conditions yielded results consistent with these unprecedented errors, with 3-D location errors >1,000 m and 2-D errors >1,600 m (Fig. 5). Further, tests with the handheld Garmin III receiver and with 4 ATS G2000 collars, at the indoor location where three POSREC collars collected 351 fixes, failed to produce errors of a magnitude approaching that of POSREC collars at the same location (Table 1).

Error Screening

We subjectively identified "good" (n=1,322) and "bad" (n=1,358) positions among data from POSREC collars deployed on mule deer and used 806 and 776, respective, "good" and "bad" fixes to generate a logistic model. A random subset of 546 and 552 fixes were retained to test classification accuracy. Stepwise selection yielded a model including three predictors, in order of entry; AngDev, the angular deviation of sequential movement vectors ($V_{n,}V_{n+1}$), LengthN_NP1, the mean length of sequential movement vectors ($V_{n,}V_{n+1}$), and RateN_NP1, the mean rate of sequential movements ($V_{n,}V_{n+1}$). Examination of variable RateN_NP1 showed that some collars were strongly influenced by variation in the time between successful GPS fixes, due to programming of uneven fix intervals, or consecutive failures of scheduled GPS fixes. To avoid overfitting and ensure broad applicability among collar programs, taxa, and study areas we chose the 2-predictor model:

$P_{bad} = logit\,(-4.77487 + 0.002656 * LengthN\_NP1 + 0.02860 * AngDev)$

A classification test at 50% probability yielded 100% concordance with 552 subjectively identified "bad" fixes and 99.1% concordance identifying 541 fixes as

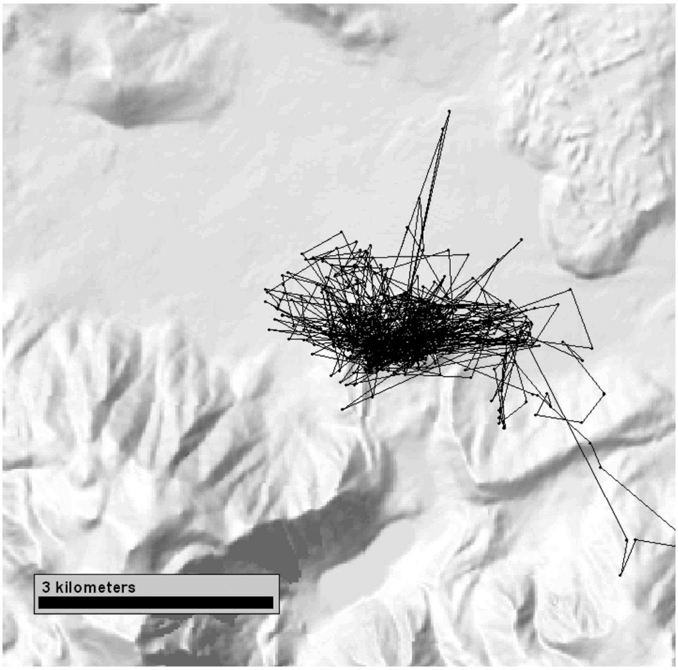

Figure 6. POSREC GPS collar movement path, mule deer RVD210, 10 Apr 2002–21 Sep 2002, generated after screening all ≥2-D fixes using the BadFix ArcView extension at the 50% probability level (n=1,064 fixes remaining).

"good," while incorrectly classifying 5 as "bad." Application of the logistic model to 89,232 movement lines generated from all ≥2-D fixes at the 50% probability level resulted in classification of 31,672 (36.0%) fixes as bad. Of these, 18,028 were 2-D, 6,407 "3-D," and 7,237 "3-D+." Screening with this approach greatly reduced the frequency of anomalous movements (Fig. 6).

DISCUSSION

Field deployment of POSREC collars generated movement patterns unlike those from any other GPS collar we have examined (e.g., Fig. 2) and showed numerous movements that were obviously improbable although inapparent when viewed solely as a swarm of points (Fig. 1). Location errors obtained from POSREC collars exceeded those of any GPS collar in our testing or reported in the literature. Evaluation of the precision of ATS, Lotek, and Televilt Simplex and Tellus collars produced location errors consistent with those reported for various conditions of terrain, canopy, and collar orientation using ATS, Lotek, and Telonics collars (D'Eon 2003, Di Orio et al. 2003, Cain et al. 2005, D'Eon and Delparte 2005).

In our effort to quantify the errors we suspected after recovering POSREC collars used in 50 animal deployments, we sought and received 191 positions from a POSREC collar (serial no. C600-176), which had been activated at an outdoor location before shipping to a customer (Q. Kermeen, Telemetry Solutions, personal communication). The maximum location error from this POSREC collar was 118.4 m (Table 1, identified as "prototype"), and characteristic of a non-defective GPS unit, but in sharp contrast to location errors we obtained from eight POSREC collars, including units with serial numbers bracketing C600-176. For example, collar C600-175, used in our optimal sky-view test, showed errors >500 m in 20.7% of 101 fixes (Fig. 5), and collar C600-219 demonstrated errors of >1,000 m in 26.6% of 45 fixes (all 2-D) at the indoor location. Data provided from collar C600-176 had been collected at 30-minute intervals, while we present data for ≥1 hour intervals, but Cain et al. (2005) reported no difference in location accuracy within this range of fix intervals. Personnel at Telemetry Solutions could not explain the difference and referred us to Televilt. We sent Televilt a summary of our data and requested the source of the unprecedented errors in every collar tested and an explanation for the normal performance of collar C600-176. Weeks later, after repeatedly requesting an explanation, we received the response, "To make it short: It is the performance of the GPS receiver that is the problem" (Anders Lindgren, Televilt/TVP Positioning AB, personal communication). We were further informed that the problem was with, "the SiRFStarI receivers, that we used in your collars," that have "a larger spread of data," and that collar C600-176, "most likely has a SiRFStarII GPS receiver," and was, "one of our prototypes." Mr. Lindgren asserted that after February 2003, collars with serial numbers >425 used the newer GPS receiver. Televilt did not acknowledge that the observed performance was unacceptable and consequently refused to discuss replacement of the 32 defective collars. If the statement about the serial numbers is accurate, some 425 POSREC-Science™ 600 collars containing the problematic GPS receiver have been sold, and can be expected to also show extraordinarily large location errors. The problem is not isolated to the 600-series collars we purchased. We located a user of POSREC-Science™ 300 collars who had documented the flaw, and were also informed that over 1,000 POSREC collars were sold in the Americas (Q. Kermeen, personal communication).

In the absence of a solution from the manufacturer, researchers are faced with a dilemma of how to salvage flawed POSREC data. Frequent location errors of several kilometers render data unacceptable for all but the most course-scaled evaluation of habitat selection or migration, thereby necessitating some type of data screening. Screening to retain only "3-D" or "3-D+" fixes magnifies inherent bias against locations where canopy cover, topography, or collar orientation preclude acquisition of high-quality fixes (Frair et al. 2004, D'Eon and Delparte 2005). While our data indicate that "3-D+" fixes have a lower frequency of errors; screening for "3-D+" fixes would remove >55% of successful fixes, yet still retain suspect locations (Fig. 3).

We created the "BadFix" extension for ArcView 3.x, which evaluates the length and angular deviation of movement vectors and applies a logistic regression model. Application of BadFix reduces habitat-associated biases by screening positions regardless of fix quality. A limitation of the screening approach we employ in BadFix is the identification of some authentic movements that approximate an out-and-back pattern. When we used the BadFix extension to screen movements of a Lotek GPS4400s collar deployed on a male puma, *Felis concolor*, 16 of 743 (2.2%) movements were flagged as "bad" at the 95% probability level, although we had no reason to believe GPS error was involved. Instead, the return of the puma to feed at a kill site approximated the out-and-back pattern the BadFix extension was designed to identify. When movements of a male bighorn sheep wearing a Televilt Telus GPS collar were screened at 95% probability, only 25 of 5150 (0.5%) of movements were identified as "bad". In both instances, a smaller sample of suspect locations were identified for further evaluation by the researcher. We believe that the screening method we present should be considered for its effectiveness at identifying potentially erroneous locations, while including more unaffected data and remaining less influenced by habitat-associated bias when compared to screening by fix quality alone.

Management Implications

We reiterate the recommendations of D'Eon et al. (2002) that researchers screen raw GPS data for anomalous positions that are clearly impossible, regardless of what model GPS collar is employed. Although an individual position may seem plausible, when it is immediately preceded and followed by near-parallel movements of unusually long distance over short times, the reliability of the fix should be questioned. Thus, we add the suggestion that a tool such as Animal Movement (Hooge and Eichenlaub 1997) be employed to aid in visual identification of anomalous fixes. We further recommend employing an automated screening tool such as the BadFix extension for larger data sets or when errors are common. We employed BadFix not only for triage of POSREC data, but for screening movement data from collars that now collect >10,000 locations. Researchers employing remote data download via direct radio may find automated screening useful for flagging artifacts of transmission we have experienced using VHF and UHF systems. The BadFix extension for ArcView 3.x is available for download from the World Wide Web at (http://arcscripts.esri.com/details.asp?dbid=14434) and is provided as open-source and may be freely modified.

We echo the recommendations of (Moen et al. 1997, Rempel and Rodgers 1997) that researchers understand factors affecting the type and precision of GPS locations, and further suggest that sample data be obtained from the model of collar being considered. Although our request for sample data was met with the provision of data from a prototype collar that was not the same as the product we purchased, requests of other manufacturers may be handled in a forthright manner. We further recommend that GPS collar users test and evaluate results of their collars before deployment. This recommendation is only practicable for collars that allow data retrieval by the user, unlike the POSREC model.

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