# Expectations and realities of GPS animal location collars: results of three years in the field

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# Expectations and realities of GPS animal location collars: results of three years in the field

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GPS collars have the potential to automatically collect large numbers of relatively accurate animal relocations. Collar costs, levels of accuracy, and satellite signal reception have been reported by other studies, but there has been little discussion of long-term performance under field conditions. Between March 1996 and April 1999, we placed 11 GPS collars on 23 individual woodland caribou *Rangifer tarandus caribou* for a total of 26 collar deployments. Reliability was highly variable; some collar deployments operated normally for their expected period of time, other deployments functioned for less than half of their expected lives. Collars attempted 41,822 locations and collected 15,247 3-D and 10,411 2-D locations, for an average acquisition rate of 59%. We recommend that researchers carefully consider project objectives, budget constraints, and available options such as differential correction and remote collar communication, before purchasing GPS collars.

*Key words: caribou, GPS, location data, movements, Rangifer, satellites, telemetry*

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Global Positioning System (GPS) collars are a relatively new tool available to wildlife managers and scientists and offer several advantages when monitoring movements and activities of large terrestrial mammals. When compared to aerial telemetry, triangulation, LORAN-C and satellite-based (i.e. Argos) methods, GPS has the fewest biases and provides the most precise locations (Hoskinson 1976, Lee, White, Garrott, Bartmann & Alldredge 1985, Garrott, White, Bartmann & Weybright 1986, White & Garrott 1986, Fancy, Pank, Douglas, Curby, Garner, Amstrup & Regelin 1988, Mills & Knowlton 1989, Findholt, Johnson, Bryant & Thomas 1996, Moen, Pastor & Cohen 1997). Also, GPS collars can relocate an animal frequently (up to once per second) during day or night regardless of weather (Rodgers, Rempel & Abraham 1996, Edenius

1997). Relative to other techniques, GPS collars have the potential for gathering greater amounts of data at a significant cost savings per location, with greater safety to the researcher, and without the temporal biases associated with weather and daylight (Springer 1979, Beyer & Haufler 1994).

Manufacturers and the published literature (e.g. Rodgers & Anson 1994, Moen, Pastor, Cohen & Schwartz 1996b, Rodgers et al. 1996) have pointed out the benefits and some of the limitations of GPS collars. Experimental trials have demonstrated that both terrain and canopy coverage can reduce the likelihood of a GPS collar acquiring the satellite signals necessary to calculate a location (Rempel, Rodgers & Abraham 1995, Moen et al. 1996b, Edenius 1997, Dussault, Courtois, Ouellet & Huot 1999). Researchers have investigated the influence of differential correction software, number and geometry of satellites, animal movement, and collar-antenna orientation on location accuracy and precision (Rempel et al. 1995, Edenius 1997, Moen et al. 1997, Rempel & Rodgers 1997, Bowman, Kochanny, Demarais & Leopold 2000). Merrill, Adams, Nelson & Mech (1998) evaluated the performance of a prototype collar over a relatively short time period, but there has been no documentation of the ability of commercially available GPS collars to meet the objectives of long-term studies (at least two years) conducted under uncontrolled field conditions. We used GPS collars to assess the movements, distribution and habitat selection of woodland caribou *Rangifer tarandus caribou* in north-central British Columbia for 3.5 years. We appraised the performance of GPS collars under field conditions and the usefulness of these collars to meet study objectives. We specifically address: 1) collar reliability; 2) data retention, recovery, and catastrophic loss; 3) location acquisition bias and realised accuracy; and 4) issues of animal welfare. We conclude with a discussion of contemporary issues relative to GPS collars and provide recommendations that researchers should consider during study design.

## Material and methods

We used GPS 1000 collars from Lotek Engineering, Inc. (Newmarket, Ontario, Canada), weighing 1.8 or 2.2 kg depending on battery size, and equipped with Motorola PVT-6 six-channel receivers. Collars were constructed to perform all positioning, communication, maintenance and sensor functions to -30°C and were designed to withstand repeated complete immersions in water (Lotek Engineering 1995). Each collar had sufficient non-volatile random access memory to store 1,680 records. Memory retention is guaranteed to -50°C and designed to retain information even if the collar ceases to function (Lotek Engineering 1995). All data were differentially correctable and were processed using the most current version of the vendor specific software N3WIN (V. 2.412).

We chose differential correction because of greater location accuracy (Moen et al. 1997). We contracted a privately operated base station to prepare the data necessary for our post-processing needs. Base station data were edited to provide just the first five minutes of every hour within which a location was recorded by the collars. This resulted in considerably smaller file sizes and reduced data storage costs (for one day 570,000 bytes compressed versus 2.5 megabytes compressed if unedited).

The 1.8-kg collars were equipped with small battery packs and were scheduled to record one location every three hours for a total of eight locations per day (56/week). The 2.2-kg collars were equipped with large battery packs and were scheduled to record one location every four hours Saturday to Thursday and every 20 minutes on every fourth hour for each Friday (60/week). We specified an 8-hour communication window seven days per week to allow data retrieval via UHF modem in the collars and the system command unit connected to a laptop computer. Based on those location and communication schedules, the communication software (GPS 1000 HOST, V. 3.04) indicated that the 1.8- and 2.2-kg collars would function for 249 and 549 days, respectively. Rodgers et al. (1996) provides additional details of the Lotek collar and a thorough description of the underlying principles of GPS.

GPS collars were deployed on female caribou in the Wolverine Herd (Heard & Vagt 1998) located approximately 250 km northwest of Prince George, British Columbia (approximately 56°N 125°W). Terrain varies, from valley bottoms at approximately 900 m a.s.l. to alpine summits at 2,050 m a.s.l., and is characterised by numerous vegetation associations. Forest types below 1,100 m are dominated by lodgepole pine *Pinus contorta*, white spruce *Picea glauca*, hybrid white spruce *P. glauca* x *P. engelmannii*, and subalpine fir *Abies lasiocarpa*. Between 1,100 and 1,600 m, a moist cold climate prevails with forest types consisting primarily of Engelmann spruce *P. engelmannii* and subalpine fir. Elevations >1,600 m are alpine tundra and are distinguished by gentle to steep windswept slopes vegetated by shrubs, herbs, bryophytes and lichens with occasional trees in krummholz form (Johnson 2000).

## Results

Between March 1996 and April 1999 we put 11 collars (three 1.8 kg and eight 2.2 kg) on 23 individual caribou for a total of 26 collar deployments (Table 1). For 22 of those deployments, collars with new batteries were placed on animals and were retrieved when the batteries were exhausted. Only four of the completed deployments lasted as long or longer than their expected battery life, and collar reliability was highly variable. Deployment 04L2 collected the greatest number of days of data (652, 119% of its expected life); in contrast, one deployment collected no useable data, and 11 others functioned for less than half of their expected lives (see Table 1).

All collars that failed prematurely (N = 18) were returned to the manufacturer for repair, refurbishment, and software/hardware upgrades if available. Most collars performed slightly better following servicing by the manufacturer, but on average individual collars functioned only 92 days longer (17% of the expected life of a collar with a large battery) than they had on their previous deployment (SD = 174, N = 15, range: -121-569 days). Only three collars (84S2, 83S2, 04L2) met or exceeded their expected battery lives on subsequent deployments.

Collars failed in one of three ways. In most cases, collars entered into a mortality mode where the VHF transmitter emitted a double beep signal. Less frequently, the VHF beacon did not indicate a malfunctioned collar. We diagnosed this type of failure only following the remote retrieval and subsequent screening of data. This occurred for four collars, resulting in 417 days of failed operation. Two collars functioned normally, but we were unable to retrieve stored data because the collar modem failed. Those animals had to be recaptured to obtain the stored data.

In all but one case, collected data were successfully stored in collars that were functioning upon animal capture or that failed prematurely. The exception was a collar with a failed modem and a dislodged backup battery (used to maintain an electrical current and re-

Table 1. Success rate of GPS collars deployed on woodland caribou in north-central British Columbia, Canada, over 37 months relative to number of days in the field and location acquisition.

| Deployment[a] | Days in field | % of expected days | No of locations | % of expected locations[b] | 3D locations (% of total) | 2D locations (% of total) | % location success (≥3 satellites) |
|---|---|---|---|---|---|---|---|
| 04L1 | 83 | 15 | 364 | 8 | 52 | 48 | 58 |
| 04L2 | 652* | 119 | 3228 | 69 | 59 | 41 | 64 |
| 77L1 | 301 | 55 | 1183 | 25 | 49 | 51 | 49 |
| 77L2 | 474 | 86 | 3281 | 70 | 75 | 25 | 90 |
| 83S1[c] | 172 | 69 | 716 | 36 | 59 | 41 | 53 |
| 83S2 | 307* | 123 | 1238 | 62 | 47 | 53 | 51 |
| 84S1[c] | 158 | 64 | 505 | 25 | 47 | 53 | 41 |
| 84S2 | 308* | 124 | 1934 | 97 | 64 | 36 | 79 |
| 84S3[d] | 209 | 84 | 1012 | 51 | 56 | 44 | 61 |
| 85L1[d] | 96 | 18 | 565 | 12 | 65 | 35 | 69 |
| 85L2 | 149 | 27 | 891 | 19 | 64 | 36 | 78 |
| 88S1[c,d] | 103 | ≈83 | 511 | 51 | 54 | 46 | 63 |
| 0EL1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0EL2 | 38 | 7 | 35 | 1 | 86 | 14 | 12 |
| 0EL3 | 129 | 24 | 876 | 19 | 83 | 17 | 93 |
| 1DL1 | 26 | 5 | 110 | 2 | 56 | 44 | 55 |
| 1DL2 | 335 | 61 | 1293 | 28 | 50 | 50 | 50 |
| B9L1 | 318 | 58 | 1856 | 39 | 55 | 45 | 74 |
| B9L2 | 197 | 36 | 778 | 17 | 53 | 47 | 52 |
| B9L3 | 213 | 39 | 1077 | 23 | 70 | 30 | 66 |
| B9L4 | 205 | 37 | 83 | 2 | 49 | 51 | 9 |
| BAL1[d] | 87 | 16 | 491 | 10 | 67 | 33 | 72 |
| BAL2 | 4 | 1 | 15 | 1 | 53 | 47 | 56 |
| BAL3 | 134 | 24 | 471 | 10 | 41 | 59 | 46 |
| BAL4 | 158 | 29 | 658 | 14 | 63 | 37 | 54 |
| E4L1 | 617* | 112 | 2487 | 53 | 49 | 51 | 52 |
| Total/$\bar{X}$ | 5473 | 51 | 25658 | 29 | 59 | 41 | 59 |

[a] Collars are named according to manufacturer identification labels followed by battery size (L = large, S = small), and number of successive deployments (e.g. 84S2: collar 84, small battery, second deployment).
[b] % of total locations that would have been recorded if collars had performed for expected lives and 100% location acquisition rate was achieved.
[c] Collars 83, 84, and 88 were equipped with single small batteries (1.8 kg) and had an expected battery life of 249 days while the remaining collars were equipped with large batteries and had an expected life of 549 days.
[d] Collars that were retrieved before battery had exhausted power, were still in the field at time of publication, or were deployed with partially used battery.
* Represents collars that functioned normally for the expected period of time.

tain all stored information following the failure of the main battery). Once we disconnected the main battery to allow safe shipping to the manufacturer, all stored data were lost (approximately six months). Generally, data retrieved from collars were free of errors and could be differentially corrected. Less than 0.5% of the retrieved data were corrupt.

Modem communication between the command unit and collar was not always successful. Except for modem failures, communication difficulties were not a product of collar design, but resulted from a poorly mounted whip antenna, slight abrasions in the connector cables, and failed laptop and command unit batteries. Because we retrieved data infrequently, it was difficult to relocate collared animals. Thus, our data retrieval costs using fixed and rotary winged aircraft were considerably more than predicted. A collar containing 1,680 records took approximately 25 minutes to upload once a link was established (≤ 10 minutes).

Over a 37-month period, the collars attempted 41,822 locations, collecting 15,247 3-D and 10,411 2-D locations for an average acquisition rate of 59%. For the 22 deployments with >100 locations, 3-D locations ranged from 41 to 83% of the total, and location success ranged from 41 to 93% (see Table 1). Three-dimensional locations had lower horizontal dilution of precision (HDOP) values ($\bar{x} = 6.7$, SD = 4.12, N = 15,247) than 2-D locations ($\bar{x} = 10.3$, SD = 75.74, N = 10,411; $t = -5.86$, df = 25,656, $P < 0.001$). An HDOP threshold of no greater than four, which is quoted as excellent satellite geometry for survey purposes and in theory should achieve a horizontal accuracy of ~5 meters (British Columbia Ministry of Environment, Lands, and Parks 1995), would require us to discard 72% of our 3-D and 36% of our 2-D locations.

Despite the collar's relatively large size, we did not witness any adverse effects on the collared female woodland caribou (~91-136 kg). Caribou were captured using a hand-held net-gun fired from a helicopter. All collars were snugly attached to minimise any side-to-side pendulum movement of the collar during running. Upon recapture, we observed some hair loss and breakage around the neck, but no bare or abraded skin. Of the 23 animals we collared, three died of natural causes at least three months after the capture date.

## Discussion

Over the 37 months that we deployed and maintained GPS collars, there were several reoccurring issues that are of contemporary importance and can be generalised to GPS collars of other types. First, field researchers should recognise that the complexity of GPS collars and the extreme conditions under which they operate will result in the premature failure of some proportion of the deployed collars. For example, in our study area, this sophisticated package of electronic hardware was subjected to variations in temperature as extreme as 45°C in a 24-hour period, rapid changes in humidity, and complete immersion in water. Reliability of GPS collars must be redefined outside that of traditional VHF collars, which are much simpler hermetically sealed devices expected to perform fewer less sophisticated functions.

Other researchers have reported collar failures within the context of much shorter studies. Moen, Pastor & Cohen (1996a) noted premature failure of all six prototype Lotek GPS 1000 collars placed on moose *Alces alces* for what was designed to be a 12-month behavioural study. Dussault et al. (1999) inferred that six of 20 Lotek 1000 collars deployed on free ranging moose operated for less than five months and thus failed prematurely. Merrill et al. (1998) placed eight prototype GPS collars constructed by Advanced Telemetry Systems, Inc. (Isanti, Minnesota) on wolves *Canis lupus* and three on white-tailed deer *Odocoileus virginianus*. Those collars were deployed with different location acquisition schedules, the longest expected life being 160 days, but eight of 11 failed prematurely.

Our experiences demonstrated that the opportunity costs of a premature collar failure could be exacerbated by other factors. First, because of infrequent animal relocations that mostly coincided with data retrieval operations, we often did not immediately diagnose a malfunction. Following detection of a collar failure, additional time was needed to arrange a recapture operation. Poor weather or unsuitable terrain (i.e. no suitable capture location) also delayed some recapture attempts. Once collars were recovered, there was an additional delay (1-2 months) associated with the diagnosis, repair and return of the collar by the manufacturer. In combination with organisation, logistics and weather delays, collar malfunction contributed to a significant loss of potential data.

At what point do reliability concerns force the researcher to reject the use of this technology? Large amounts of money and time may be sacrificed, and despite best efforts, insufficient data may be collected to answer pre-defined research questions. In our study, only 18% of the collars functioned properly to battery exhaustion. Despite these setbacks, we did collect nearly 26,000 locations over a wide enough time period to meet our study objectives of describing the multi-scale movements and habitat selection patterns of woodland caribou (Johnson 2000). At our average location acquisition rate of 59%, normal operation of all collars with field replacement of batteries would have resulted in approximately 48,000 locations. To ensure that study objectives are met, a specific collar's reliability should be estimated based on the best available information, and a pre-determined number of collars should be kept in reserve to replace collars that fail prematurely. This strategy will maintain a minimum number of collars in the field while failed units await replacement and repair.

Depending on terrain and vegetation, a GPS receiver may or may not be capable of obtaining signals from a minimum of three satellites and calculating a location. This is an inherent quality of all GPS devices, but can have significant implications for the interpretation of use versus availability statistics and other frequency-related measures (Dussault et al. 1999). Before electing to use this technology we recommend that researchers assess the performance of GPS devices across the habitat types animals are expected to use. Published studies for free-ranging moose reported location acquisition rates of 58% for southern Quebec, Canada (Dussault et al. 1999), 75% for northern Sweden (Edenius 1997), 83-96% for southern Alaska, USA (Moen et al. 1996b), and 76% for western Ontario, Canada, (Rempel et al. 1995). Merrill et al. (1998) reported acquisition rates of 26-95% for free-ranging wolves and white-tailed deer in central Minnesota and central Alaska, USA. Collars on captive white-tailed deer in east-central Mississippi collected locations during 85% of attempts (Bowman et al. 2000). Variability between individuals in the same area was well demonstrated by Poole & Heard (1998) reporting acquisition rates of 79 and 27% for two female goats *Oreamnos americanus* located in the Rocky Mountains of east-central British Columbia, Canada.

In general, large diameter, dense and tall vegetation, and steep topography will degrade reception of satellite signals (Rempel et al. 1995, Moen et al. 1996b, 1997, Edenius 1997, Rempel & Rodgers 1997, Dussault et al. 1999, Bowman et al. 2000). Hence, large variation in location acquisition rates could be expected within and among study areas. We suspect that variation in location success for our collared animals (41-93%) was due to differences in habitat use, with collars on caribou living primarily in alpine areas having higher location acquisition rates than those on caribou living in the forest.

Capability to remotely retrieve data and diagnostics is an option available from three manufacturers of GPS collars (Lotek Engineering, Newmarket, Ontario, Canada; Televilt International AB, Lindesberg, Sweden; Telonics, Inc., Mesa, Arizona, USA). Additionally, GPS collars from Lotek Engineering can be reprogrammed remotely with new location and communication schedules. The utility of these features depends on the focal species and study duration. If animal capture is inexpensive and can be performed year-round, or information about animal movement is required only for short periods, then costs related to user-collar communication may not be warranted. We recommend remote data retrieval when study length exceeds collar memory and animals are difficult to capture or where animals periodically move large distances and are difficult to relocate. Ability to alter collar activity schedules is an asset where sampling strategies need to be adjusted in accordance with unpredictable animal behaviour.

Differential correction is an option for purchasers of GPS collars. Although differential correction can increase precision, suboptimal satellite geometry can degrade the accuracy of many locations beyond that quoted by the manufacturer. Differential correction also has many often unforeseen drawbacks that can add to project costs, or reduce immediate usefulness of the data. Furthermore, the recent deactivation of selective availability (the main source of controllable error) reduces the utility of differential correction substantially. Researchers should not assume that differential correction is necessary for all projects, but rather consider the additional accuracy and precision within the context of the hypotheses to be tested (Rempel & Rodgers 1997, Hulbert & French 2001).

We opted for differential correction because we wanted to mitigate the effects of selective availability while addressing questions relative to fine-scale movements and habitat use. We did not, however, anticipate a number of costs that eclipsed those directly related to software and base station data purchases. First, differential correction required a large amount of computing time. Second, when base station data were missing, N3WIN did not provide a non-differentially corrected location. Third, differential records required more memory, per location, than non-differential records. A collar collecting non-differential locations could store 3,640 records, whereas a collar collecting the data necessary for correction could store only 1,680 records. Differential correction requires more frequent retrieval of data, greater power demands, and, therefore, results in a reduction in the collar's field life.

## Conclusions

Several of the published works discussing GPS collars have concluded with statements such as "GPS-based animal-location systems will set a new standard for habitat-resource utilisation studies of large animals over the next five to 10 years" (Rodgers et al. 1996: 565). Our research, although not reported here, also has demonstrated that GPS collars can provide insights into small-scale movements, infrequent behaviours such as migration events, and activities during dark and inclement weather (Johnson 2000). There is, however, a trade-off between location frequency and cost. At this point in their development, field-operation and GPS-collar maintenance require large amounts of time and money. Furthermore, there are still limitations related to the performance and reliability of GPS collars. In some cases, broad management objectives such as home range determination or habitat use may be achieved with frequent monitoring of conventional VHF-collars. Aerial or ground telemetry has fewer data-related risks (i.e. catastrophic loss) and complications, has more predictable costs, and will likely result in a larger number of individuals collared at any one time. This, however, must be weighed against the utility of relatively frequent accurate locations regardless of daylight or weather. Ultimately, the wildlife professional must choose the tool that best meets study objectives and budget.

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## References

Beyer, D.E., Jr. & Haufler, J.B. 1994: Diurnal versus 24-hour sampling of habitat use. - Journal of Wildlife Management 58: 178-180.

Bowman, J.L., Kochanny, C.O., Demarais, S. & Leopold, B.D. 2000: Evaluation of a GPS collar for white-tailed deer. - Wildlife Society Bulletin 28: 141-145.

British Columbia Ministry of Environment, Lands, and Parks 1995: British Columbia standards specifications and guidelines for resource surveys using global positioning system (GPS) technology. - Ministry of Environment, Lands, and Parks, Surveys and Resource Mapping Branch, Victoria, British Columbia, Canada, 47 pp.

Dussault, C., Courtois, R., Ouellet, J-P. & Huot, J. 1999: Evaluation of GPS telemetry collar performance for habitat studies in the boreal forest. - Wildlife Society Bulletin 27: 965-972.

Edenius, L. 1997: Field test of a GPS location system for moose Alces alces under Scandinavian boreal conditions. - Wildlife Biology 3: 39-43.

Fancy, S.G., Pank, L.F., Douglas, D.C., Curby, C.H., Garner, G.W., Amstrup, S.C. & Regelin, W.L. 1988: Satellite telemetry: a new tool for wildlife research and management. - U.S. Fish and Wildlife Service Resource Publication No. 172, 54 pp.

Findholt, S.L., Johnson, B.K., Bryant, L.B. & Thomas, J.W. 1996: Corrections for position bias of a LORAN-C radiotelemetry system using DGPS. - Northwest Science 70: 273-280.

Garrott, R.A., White, G.C., Bartmann, R.M. & Weybright, D.L. 1986: Reflected signal bias in biotelemetry triangulation systems. - Journal of Wildlife Management 50: 747-752.

Heard, D.C. & Vagt, K.L. 1998: Caribou in British Columbia: a 1996 status report. - Rangifer Special Issue Number 10: 117-123.

Hoskinson, R.L. 1976: The effect of different pilots on aerial telemetry error. - Journal of Wildlife Management 40: 137-139.

Hulbert, I.A.R. & French, J. 2001: The accuracy of GPS for wildlife telemetry and habitat mapping. - Journal of Applied Ecology 38: 869-878.

Johnson, C.J. 2000: A multi-scale behavioural approach to understanding the movements of woodland caribou. - PhD thesis, University of Northern British Columbia, Canada, 210 pp.

Lee, J.E., White, G.C., Garrott, R.A., Bartmann, R.M. & Alldredge, A.W. 1985: Assessing accuracy of a radiotelemetry system for estimating animal locations. - Journal of Wildlife Management 49: 658-663.

Lotek Engineering 1995: LOTEK The GPS Animal Location System User's Manual (Release 2: January 1995). - Lotek Engineering, Newmarket, Ontario, Canada, 46 pp.

Merrill, S.B., Adams, L.G., Nelson, M.E. & Mech, L.D. 1998: Testing releasable GPS radiocollars on wolves and white-tailed deer. - Wildlife Society Bulletin 26: 830-835.

Mills, L.S. & Knowlton, F.F. 1989: Observer performance in known and blind radiotelemetry accuracy tests. - Journal of Wildlife Management 53: 340-342.

Moen, R., Pastor, J. & Cohen, Y. 1996a: Interpreting behavior from activity counters in GPS collars on moose. - Alces 32: 101-108.

Moen, R., Pastor, J. & Cohen, Y. 1997: Accuracy of GPS telemetry collar locations with differential correction. - Journal of Wildlife Management 61: 530-539.

Moen, R., Pastor, J., Cohen, Y. & Schwartz, C.C. 1996b: Effects of moose movement and habitat use on GPS collar performance. - Journal of Wildlife Management 60: 659-668.

Poole, K.G. & Heard, D.C. 1998. Habitat use and movements of mountain goats as determined by prototype GPS collars, Robson Valley, British Columbia. - Biennial Symposium of the Northern Wild Sheep and Goat Council 11: 22-35.

Rempel, R.S. & Rodgers, A.R. 1997: Effects of differential correction on accuracy of a GPS animal location system. - Journal of Wildlife Management 59: 543-551.

Rempel, R.S., Rodgers, A.R. & Abraham, K.F. 1995: Performance of a GPS animal location system under boreal forest canopy. - Journal of Wildlife Management 61: 525-530.

Rodgers, A.R. & Anson, P. 1994: Animal-borne GPS: tracking the habitat. - GPS World 5: 20-32.

Rodgers, A.R., Rempel, R.S. & Abraham, K.F. 1996: A GPS-based telemetry system. - Wildlife Society Bulletin 24: 559-566.

Springer, J.T. 1979: Some sources of bias and sampling error in radio triangulation. - Journal of Wildlife Management 43: 926-935.

White, G.C. & Garrott, R.A. 1986: Effects of biotelemetry triangulation error on detecting habitat selection. - Journal of Wildlife Management 50: 509-513.