Accuracy, Precision, and Performance of Satellite Telemetry for Monitoring Wolf Movements

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We placed 23 satellite platform transmitter terminals (1.08–1.22 kg) on wolves in northwest Alaska during 1987 through 1991. Male and female wolves aged 10 months to eight years were monitored with no apparent adverse effects on them. We obtained 3,801 relocations from the 23 transmitters, an average of 29 relocations/month from each. Transmitters were programmed to operate four to six hours every two days and had a mean life span (including days before and after use on a wolf) of 253 days (range = 67–482 days). Average life span while attached to wolves was 181 days (range = 50–366 days). Accuracy of 1,885 relocations at seven known sites varied among transmitters and averaged 336 and 728 m for best and low quality relocations, respectively. The estimated locations from several transmitters were biased toward south and west directions. Costs (1992) per satellite relocation averaged about $44 U.S., in comparison to about $166 with conventional telemetry methods using fixed-wing aircraft. Satellite telemetry has great potential for providing improved data sets for evaluation of wolf territory sizes and movements, but currently lacks accuracy and precision for detailed habitat or landscape use assessments.

Introduction

Satellite telemetry has become a widely accepted tool for studying movements of large mammals and birds (Fancy et al. 1988, 1989, Harris et al. 1990), particularly where logistics or movement patterns make conventional telemetry methods costly or impractical. The U.S. Fish and Wildlife Service and the Alaska Department of Fish and Game have cooperated since 1984 to develop, test, and refine the use of satellite telemetry for studying large ungulates and predators. Advances in transmitter miniaturization and power supplies have made satellite transmitters feasible for studies of smaller species such as wolves (*Canis lupus*). In early 1987, Telonics Inc. (Mesa, Arizona) developed a satellite transmitter that used three C-cell batteries. The 1,200 g transmitter package (includes satellite transmitter, its power supply, a very high frequency (VHF) tracking beacon and its power supply, packaging, and the attachment collar) were the smallest available and appeared light enough to be used safely on wolves. Service Argos refers to a satellite transmitter as a platform transmitter terminal (PTT).

Several investigators have examined the accuracy and precision of PTTs (Mate et al. 1986, Craighead and Craighead 1987, Fancy et al. 1988, Stewart et al. 1989, Harris et al. 1990, Keating et al. 1991), but only the latter three reports provided evaluations of the systems after 1987 when Service Argos made improvements in calculating locations and quality indices (Keating et al. 1991). Of the latter three studies, only Keating et al. (1991) evaluated the system using PTTs as small as ours. We report on the accuracy and precision of the Argos system, and evaluate the performance of PTTs used on free-ranging gray wolves in northwest Alaska during 1987–1991. We define accuracy as the closeness of an estimated relocation to the true location, whereas precision refers to the repeatability of the measurement.

Study Area and Methods

We placed PTTs on free-ranging wolves in northwest Alaska (65° 15', 67° 30' N; 156° 30', 160° 00' W). The area encompassed Kobuk Valley National Park, Selawik National Wildlife Refuge, portions of Noatak National Preserve, and Koyukuk National Wildlife Refuge. The study area has been described by Ballard et al. (1990) and Ballard (1993).

Fancy et al. (1988) and Harris et al. (1990) provided detailed accounts of the history, use, and applications of the Argos Data Collection and Location System (DCLS). Argos instruments on two polar-orbiting satellites pass over Alaska approximately 24 times each day. The satellites receive signals from the PTTs in the ultrahigh frequency (UHF) range and relay data to ground stations located in Alaska, Virginia, and France. Data are provided to users monthly on computer tapes but can be accessed approximately three to eight hours following a satellite overpass using a telephone modem and computer links (Fancy et al. 1988). Each satellite relocation is given a location quality index (NQ) by Argos reflecting its expected accuracy; NQ 3, 68% of locations reportedly accurate within 150 m; NQ 2, 68% of locations reportedly accurate within 350 m; NQ 1, 68% of locations reportedly accurate within 1,000 m; and NQ 0, quality of relocations determined by user (Service Argos 1989). The quality of each relocation depends on the number and quality of messages received during an overpass, stability of the PTT's oscillator, geometry of the overpass, and other factors (Fancy et al. 1988, Harris et al. 1990, Keating et al. 1991). Standard processing by Argos includes only high quality relocations (i.e., NQs 1–3). Other processing options include nonguaranteed (NQ 0), which provides additional relocations, but the error associated with the relocation is not specified by Argos and must be determined by the user. The NQ 0 processing costs an additional $1.25/day/PTT and provides the greatest number of relocations, but many are inaccurate with no objective methods for separating accurate from inaccurate relocations. Keating et al. (1991) reported errors ranging from 128 to 396 170 m for NQ 0 relocations. We performed a preliminary analysis of our NQ 0 relocations and also found errors up to several km. Consequently, we excluded the 3,573 NQ 0 relocations (48% of all locations) from our accuracy and precision analyses and focused only on NQs 1–3.

A PTT can be programmed to transmit to the satellite with a variety of on/off time periods. The 13 units deployed in 1988 and 1989 transmitted for six hours daily through the first 30 days and then six hours every two days (six hours on/42 hours off) until battery exhaustion, while the 10 units deployed in 1987 and 1990 transmitted for six hours every two days until battery exhaustion. Units deployed in 1987 and 1990 had a life expectancy of 181 days whereas those deployed in 1988 and 1989 had an expected life span of 157 days. Two of the PTTs deployed in 1988 had a four-hour transmission schedule after the initial 30-day period and their life expectancy was 185 days. There was no significant difference ($t = -2.4$, $P < 0.05$) in the number of locations provided by four- or six-hour transmissions, so the data were pooled.

We exposed 1–1.5 cm of the UHF antenna on each unit prior to activating each PTT because a partially exposed antenna may increase location accuracy (S.G. Fancy and W.B. Ballard, unpubl. data). The latter relationship is most directly related to signal strength (W.P. Burger, Telonics Inc., Mesa, Arizona, pers. commun.). Each collar was cut and the antenna was pulled out so it remained flush up against the collar.

Each PTT contained a mercury tip switch to monitor short and long-term activity, a temperature sensor that provided the internal temperature of each canister, a low voltage indicator to indicate when batteries were becoming depleted, and a conventional VHF transmitter to allow each animal to be relocated by conventional radiotelemetry. The UHF and VHF transmitters had separate power supplies and antennas. Descriptions of temperature and activity sensors and wolf activity patterns as determined by satellite telemetry are described by Fancy and Ballard (this volume).

Four generations of PTT collar design were used during the study. The initial prototype PTT used in 1987–1988 weighed 1.22 kg, was rather bulky, and could only be deployed on adult wolves. The design was modified to reduce the size and weight of the units. The first modification involved eliminating the urethane shock buffer from the front and rear of the canister housing the transmitter. The sides of this second generation PTT (1.16 kg) were encased in urethane to protect the antenna as it exited the canister before entering the collar. On several collars the urethane was separating from the canister. If glass to metal feed-throughs for the antennas were broken as this urethane separated from the canister, water could potentially enter the canister. For the third generation (1.08 kg), the urethane caps were eliminated and the antenna exited the top of the canister directly into the collar. The fourth generation (1.10 kg) involved narrowing the depth of the canister and the collar.

Wolves were immobilized for deployment of PTTs by darting from helicopters using methods described by Ballard et al. (1982, 1991b). Conventional VHF transmitters were deployed on one to three other members of a pack to aid in locating the pack and the individual with the PTT. Prior to deployment, when wolves died and after the PTTs had been retrieved, they were allowed to continue transmitting from fixed known locations. All PTTs were unobstructed, transmitted from the ground, and were not on a wolf. Service Argos requires that an average elevation of transmission be designated prior to deployment. The designated elevation for this study was sea level, while the elevation of known locations averaged 29.4 m (range = 0–91 m). Known locations were determined from 1:63,360 scale U.S. Geological Survey maps. Satellite and known locations were converted to Universal Transverse Mercator (UTM) coordinates and differences between them were calculated using LOTUS spreadsheets.

Statistical Tests

We analyzed locations with NQs 1–3 separately because all previous studies have found significant differences in location errors among each NQ category. For each NQ category, we used each combination of PTT, year, and known location as a treatment. Homogeneity of variances was tested within each NQ category with Bartlett-Box F test (Snedecor and Cochran 1973). Unequal variances were found ($P < 0.001$)

within each category. Differences among treatments by NQ category were then analyzed using the Kruskal-Wallis test (Ott 1988). If significant differences ($P < 0.05$) were detected, we performed multiple comparison of treatment means using Mann-Whitney U tests (Ott 1988).

Location errors were compared among locations for each PTT within the same year using Mann-Whitney tests (Ott 1988). Results of these analyses were pooled, and we report differences using Fisher's combined probability tests of significance (Sokal and Rohlf 1969). Location error was also evaluated by year using the same statistical procedures described above by comparing errors for each PTT positioned at the same site between years. Proportional distributions were analyzed using log-linear models and Chi-square analyses of log-transformed odds ratios. Directional error and bias were measured with Hotelling's one-sample test (Batschelet 1981:144). Because of differences in location errors among transmitters and locations, differences in location quality, and whether the PTTs were transmitting on or off a wolf, different subsets of data were tested for each analysis.

Results

Performance

During spring 1987, we used two prototype PTTs on gray wolves in northern Alaska (Ballard and Fancy 1988). One PTT failed after one month (not included), but the other performed flawlessly for 13 months (Ballard and Fancy 1988). During 1988–1990, an additional 22 PTTs were used on wolves of various sizes in northwest Alaska, and on both sexes, ranging in age from 10 months to eight years and weighing 28.6 to 51.7 kg. None of the females equipped with PTTs denned during the study. Subsequent visual observations from fixed-wing aircraft and physical examinations during re-collaring suggested none of the wolves were adversely affected by the size or weight of the PTTs. However, the collars (50.0–68.3 mm in width) caused excessive rubbing of guard hairs and underfur and would probably significantly reduce the value of the hides of animals shot or trapped and commercially sold.

During April 1987 through May 1991, signals from the 23 wolf PTTs were received by satellite during 14,669 overpasses and 7,374 relocations (NQs 0–3) were calculated. An additional 7,295 sets of sensor data without relocations were obtained. Satellites received an average of 1.5 signals/overpass in which at least one signal was received. Fewer relocations/month were obtained for each PTT when deployed on a wolf than when free-standing ($X^2 = 1,473$, $P < 0.001$). An average of 29 ± 18 relocations (n = 106 months) with sensor data was provided per month of transmission while attached to the wolf compared to 51 ± 29 relocations/month (n = 31 months) when not attached. We obtained 3,801 relocations ranging in quality from NQ 1–3 from the 23 PTTs used on free-ranging wolves; NQ 1 = 2,869, NQ 2 = 879, and NQ 3 = 53. Each PTT transmitted (in contrast to life span that includes both transmission and nontransmission days) an average of 72 days ± 46 (range = 9–148 days) and provided an average of 2.2 ± 0.7 relocations/day of transmission (range = 1.2–3.9 relocations).

Average total life span (includes periods on and off wolves) for the 23 wolf PTTs used during 1987 through 1991 was 253 ± 128 (SD) days (range = 67–482 days). Average life span while actually on a wolf, including wolves that died prior to PTT failure, was 181 ± 112.7 days (range = 50–366 days, n = 23). The latter value did not differ from an average life span of 187 ± 109 days (range = 50–366 days, n = 14) for PTTs that expired while attached to a wolf. The latter two values were similar to the theoretical life span predicted by Telonics based on battery life with a duty cycle of six hours on and 42 hours off. Longer life spans for PTTs not attached to animals have been reported previously by Fancy et al. (1988) and Harris et al. (1990). Variance in life spans of PTTs depend primarily on variability among individual battery packs, specific current drains of electronics, repetition periods, duty cycles, operating temperatures, and standing voltage wave ratios. The latter term refers to the proximity of the antenna to the animal that causes the antenna to become detuned. Power output of the PTT automatically adjusts to overcome antenna detuning and, consequently, can increase battery drain by up to approximately 20% (S.M. Tomkiewicz, Telonics Inc., Mesa, Arizona, pers. commun.).

Average life spans for PTTs that ceased operation while attached to wolves differed significantly by year of deployment ($H = 5.4$, $P = 0.067$). Excluding the 1987 prototype PTT (n = 1,319-day actual life span), which functioned for 175% of the expected battery life, average life span for this subset of PTTs declined each year; 1988 = 259 ± 86 days (n = 4), 1989 = 211 ± 106 days (n = 5), and 1990 = 104 ± 65 days (n = 5). PTTs deployed during 1988 through 1990 achieved 165, 134, and 57% of their expected battery life, respectively. Premature battery failure or failure of sockets which connect microprocessors to the main board could have been responsible for the poor performance of the PTTs during 1990 (W.P. Burger, Telonics Inc., pers. commun.).

After one wolf died in 1990 and remained motionless for several days, the PTT ceased transmitting to the satellite. When the PTT was retrieved, successful transmission was resumed. Telonics examined the PTT and was unable to duplicate the failure, and could not detect any problems. It was possible that the antenna radiation pattern on the dead wolf prevented signal reception at the satellite (W.P. Burger, Telonics Inc., pers. commun). Also, faulty microprocessor plugs and variation in batteries were suspected reasons for premature failure of PTTs deployed on grizzly bears (*Ursus arctos*) in northwest Alaska during the same time period as this study (Ballard et al. 1991d). J. Weaver (Univ. of Montana, Missoula, pers. commun.) and P. Paquet (Jasper Natl. Park, Jasper, Alberta, pers. commun.) also had shorter life spans for PTTs manufactured in 1990 (n = 2) compared with those manufactured in 1989 (n = 2).

Very high frequency transmitters in the PTT canister were inferior to conventional VHF transmitters in terms of signal strength. J. Weaver (Univ. of Montana, pers. commun.) reached a similar conclusion for similar PTTs. Initially, most VHF signals from PTTs could be received from an aircraft at a distance of 10–20 km, but reception distance declined with time. When the UHF units expired, the VHF transmission distance was < 1 km, and in several cases the units could not be heard until the aircraft flew directly overhead.

Accuracy and Precision

Average location error for NQs 1–3 for all PTTs (n = 16) at seven known locations during three years of deployment was 577 ± 610 m (n = 1885). Mean errors for locations with NQs 1, 2, and 3 were 728 ± 757, 551 ± 528, and 336 ± 220 m, respectively. We found significant differences ($\underline{P} < 0.05$) for location errors among PTTs (Table 1). However, there were no significant differences in location errors by NQ for location (NQ 1 $\underline{P} = 0.53$, NQ 2 $\underline{P} = 0.84$, and NQ 3 $\underline{P} = 0.42$) or year of deployment (NQ 1 $\underline{P} = 0.23$, NQ 2 $\underline{P} = 0.73$, and NQ 3 $\underline{P} = 0.95$) when each PTT was analyzed separately. Average error by location ranged from an average of 259 m for NQ 3 at Kateel River to 1,049 m for NQ 2 at Kotzebue, Alaska (Table 2). Sixty-eight percent of the relocations were < 734, < 556, and < 360 m from the known location for NQs 1 through 3, respectively.

We compared the frequency of relocations by NQ for PTTs on and off the wolf. A three-way log-linear model (PTT X NQ class X on or off animal) was fitted to examine whether the distribution of relocations between NQ codes was independent of the PTT and/or whether the PTT was on or off a wolf (Agresti 1984). The full model could not be rejected ($\underline{P} < 0.001$) indicating the distribution of NQ codes was not independent of PTT nor whether it was deployed on or off a wolf. Location quality code distributions differed among PTTs when the collar was on or off a wolf. As an exploratory measure, a two-way log-linear model (PTT X NQ class) was fitted to NQ code distributions for when PTTs were deployed on wolves, and a separate model for when PTTs were not on wolves. Neither full two-way model was rejected ($\underline{P} < 0.001$ and $\underline{P} < 0.001$, respectively), indicating that the distribution of NQ codes was dependent on the individual PTT and whether it was on or off the wolf.

There were significant directional error biases in locations reported for different PTTs and locations ($\underline{P} < 0.05$). Generally, locations provided by the Argos system were biased toward the south and west (Table 3). All NQ 2 and 3 relocations with the exception of those from Shungnak had significant directional biases ($\underline{P} < 0.05$), 71% of which were toward southerly and westerly directions. Surprisingly, NQ 1 relocations for both Selawik and Kotzebue were not significantly ($\underline{P} > 0.05$) biased.

Lastly, we tested the hypothesis that the accuracy of relocations could be improved by exposing the UHF antenna slightly outside the collar material. We placed one PTT on a domestic dog at a known location (termed Experiment 1), and after several days of transmission, we exposed the UHF antenna and the PTT was again allowed to transmit (Experiment 2). We then removed the PTT from the dog and allowed the PTT to transmit from the same location (Experiment 3). Significant differences in location error were found between Experiment 1 ($\bar{x}$ = 3,695 ± 1,829 m, n = 30) and experiments 2 ($\bar{x}$ = 2,624 ± 774 m, n = 23) and 3 ($\bar{x}$ = 2,268 ± 450 m, n = 20)(Mann-Whitney U test, $\underline{P} < 0.002$). No differences were detected between experiments 2 and 3 ($\underline{P} = 0.64$). These analyses suggest exposing the UHF antenna can improve the quality of relocations.

Discussion

Numerous factors influence the accuracy of relocations obtained with satellite telemetry. Harris et al. (1990) reported that PTT oscillator instability, changes in PTT elevation, animal movement, insufficient number of transmissions reaching the satellite, errors in satellite orbital data, computational algorithms, and mapping methods affected location accuracy. Fancy et al. (1988) and Harris et al. (1990) also found that changes in ambient air temperature, antenna size, deployment on animals versus transmission from inanimate positions, and maximum satellite elevation during an overpass affected accuracy of satellite relocations. Harris et al. (1990) reported that there may be an interaction among PTT, satellite overpass, and whether the PTT was on or off an animal with regard to reductions in precision of relocations. Keating et al. (1991) also had similar results. Our findings agree with those of Fancy et al. (1988), Harris et al. (1990), and Keating et al. (1991).

Directional bias in satellite locations has been reported in all studies that have evaluated accuracy and precision (Fancy et al. 1988, Harris et al. 1990, and Keating et al. 1991). Fancy et al. (1988) reported west and northwest biases while Keating et al. (1991) reported longitudinal biases primarily in a southeasterly direction. Fancy et al. (1988) suggested that part of the bias could be the result of using U.S. Geological Survey topographic maps, which use the NAD27 projection of the earth whereas Argos uses the WGS84 system. However, Harris et al. (1990) reported that even after adjusting the data to account for the differences in the two projections, significant biases remained, but errors were small (i.e., <150 m) in relation to total variation. Keating et al. (1991) also adjusted for type of map projection and concluded that directional errors were largely caused by distance from satellite and differences in estimated and actual PTT elevation. P.Y. Letraon (Service Argos, Landover, Maryland, unpubl. data) estimated that errors in cal-

Table 1. Summary of average location error of 16 wolf PTTs transmitting from known fixed locations in northwest Alaska, 1988–1991.

	Quality of Relocation[1]											
	NQ1			*NQ2*			*NQ3*			*ALL*		
Radio No.	*Mean*	*SD*	n	*Mean*	*SD*	n	*Mean*	*SD*	n	*Mean*	*SD*	n
1	930	1169	65	722	498	56	457	309	28	763	855	149
2	818	621	34	595	581	83	341	198	74	536	508	191
3	1009	1176	17	1100	910	14	280	190	6	925	1001	37
4	1049	992	29	586	410	45	409	220	21	688	667	95
5	815	570	102	656	553	53	422	204	26	712	544	181
6	421	329	114	370	196	37	477	384	15	415	310	166
7	550	836	8	556	609	8	452	151	4	533	632	20
8	704	623	13	592	429	14	452	252	4	621	498	31
9	1283	1140	10				256	40	2	1112	1106	12
10	497	270	7	456	179	9	342	86	4	448	202	20
11	589	586	282	368	267	202	263	139	191	431	435	675
12	811	823	24	619	700	33	407	197	12	657	703	69
13	1188	853	29	557	679	36	384	164	7	794	791	72
14	1026	984	19	808	992	38	384	318	6	834	952	63
15	1405	1560	14	754	567	15	316	131	10	875	1071	39
16	905	672	11	561	342	48	757	609	6	637	451	65
All	728	757	778	551	528	691	336	220	416	577	610	1885

1 NQ = location quality index

Table 2. Summary of average location error by location of transmission for 16 wolf PTTs in northwest Alaska, 1988–1991.

	Quality of Relocations											
	NQ1			*NQ2*			*NQ3*			*All*		
Location[1]	*Mean*	*SD*	n	*Mean*	*SD*	n	*Mean*	*SD*	n	*Mean*	*SD*	n
Selawik Cabin	967	962	290	618	584	408	414	258	188	689	719	886
Pick River	642	582	16	576	419	26	327	213	26	496	421	68
Kotzebue	907	1102	21	1049	899	15	372	303	8	858	949	44
Shungnak	333	163	5	683	382	9	267	123	2	522	349	16
Rabbit Mtn.	373	272	94	288	139	22	269	140	5	353	250	121
Kateel River	576	538	268	359	242	198	259	137	187	420	400	653
Kiliovilik	781	580	84	1097	749	13				824	611	97
All	728	757	778	551	528	691	336	220	416	577	610	1885

1 Latitude-Longitude (decimal degrees) and elevations of known sites was as follows: Selawik Cabin = 66.6065N — 159.0918 W, 1 m; Pick River = 66.5219 N — 156.4340 W, 34 m; Kotzebue = 66.8987 N — 162.5970 W, 0 m; Shungnak = 66.8880 N — 157.1359 W, 45 m; Rabbit Mtn. = 66.6361; N — 158.8071 W, 36 m; Kateel River = 65.3315 N — 158.5909 W, 91 m; and Kiliovilik = 66.4641 N — 158.6720 W, 19 m.

Table 3. Summary of average directional bias of wolf PTTs by location and NQ category as determined from known locations in northwest Alaska, 1988–1991.

Location	NQ1 Mean Angle	NQ1 n	NQ2 Mean Angle	NQ2 n	NQ3 Mean Angle	NQ3 n
Pick River	334*	16	328*	26	330*	26
Shungnak	277	5	222	9		
Kateel River	237*	268	224*	198	237*	187
Kiliovilik River	240*	84	225*	13		
Rabbit Mt.	237*	94	202*	22	223*	5
Selawik	195	290	211*	408	195*	188
Kotzebue	103	21	135*	15	94*	8

* Significant directional bias ($P < 0.05$).

culated locations could be 0.5–3.5 the error in actual versus assumed altitude of the PTT. Because our baseline altitude was at sea level and most of the PTTs were tested at Selawik cabin this source of error should have been minimal in this study.

Keating et al. (1991) reported 68 percentile errors of 1,188 m, 903 m, and 361 m for NQs 1 through 3, respectively, in comparison to expected precision (Service Argos 1984, Clark 1989) of 1,510 m, 528 m, and 226 m, respectively. Our errors of 551 m and 336 m for NQs 2 and 3 were similar to those reported by Service Argos (1984) and Keating et al. (1991), but our mean error of 728 m for NQ 1 was considerably lower than those reported previously. Some of the reported differences were due to a less rigorous study design than that of Clark (1989) or Keating et al. (1991) and because Argos estimates are based on independent distributions of x and y coordinates whereas our estimates were based on joint distributions. Also, relatively small sample sizes may have influenced our results. Additionally, our collars were configured differently than those used in previous studies, and our study was conducted farther north. Therefore, system performance should have benefited from a higher number of total overpasses and overpasses with good pass geometry than at lower latitudes. We should have had more locations with more overpasses and a higher probability for getting more NQ 3 locations.

Potentially large variation in location errors among wolf PTTs could complicate data interpretation depending on study objectives. Users of wolf PTTs cannot afford the time or funds to conduct accuracy and precision checks for each study area and individual PTT. At the least, however, users should allow each PTT to transmit for several days prior to deployment so that gross differences in PTT accuracy can be assessed.

Keating et al. (1991) stated that use of satellite telemetry for assessing "localized movements and habitat use" is an alluring alternative to conventional telemetry, but substantial improvements in data quality are necessary before such studies can be conducted. We add that it is also a method that has become "in vogue" and prestigious to use even though some study objectives might be more efficiently accomplished with conventional telemetry or other methods. Even assuming average location errors of 300–700 m, such data have limited use, particularly when examining habitat utilization, unless an investigator is only interested in broad associations. However, assessing localized movements and habitat use is a matter of scale that is dependent on the species being studied and its landscape. If patches of prey or habitat are distributed coarsely (i.e. > 2 km) across a landscape and the study animal moves great distances each day (e.g. 10–20 km) then satellite telemetry may provide data of sufficient precision to allow assessment of habitat use.

Investigators must carefully consider study objectives before deciding to use satellite telemetry. In our case, use of satellite telemetry appeared justified because weather, short daylight, and winter logistics precluded location of wolves frequently enough with conventional telemetry to accurately determine movements. In northern latitudes, wolves either occupy large territories (i.e., 1,000 to 2,000 km^2) or they travel long distances (hundreds or thousands of km) following migratory caribou (*Rangifer tarandus*). Maintaining radio contact would be difficult and perhaps impossible. The location errors we discovered are probably acceptable for estimating wolf territory sizes or tracking animal movements under those circumstances. Territory sizes and movement characteristics are probably more accurately described with satellite telemetry than with conventional radiotelemetry, particularly in northern latitudes where territories are larger, because of the continuous uniform monitoring. A preliminary analysis for one wolf pack indicated the annual territory size determined by satellite data (n = 415) was approximately 75% larger than that found through conventional radiotelemetry (n = 38) (Ballard and Fancy 1988). Relocations obtained with conventional telemetry are often clumped, auto-correlated, and too infrequent to accurately assess territory or home range sizes.

Unless PTT-equipped wolves were accompanied by other wolves equipped with conventional VHF transmitters, relocation of animals by the PTT VHF transmitter was nearly impossible. Because VHF and UHF units are contained within the same collar, the length of the VHF antenna is reduced from 457 mm to 229 mm, resulting in a reduction in transmission range of approximately 75%. Keating et al. (1991) suggested that signals from each unit might interfere with each other and result in both poorer quality satellite relocations and reduced range from the VHF unit. However, there appears to be no basis for this hypothesis, and the relatively short antenna explains the lack of range of the VHF transmitter (S.M. Tomkiewicz, Telonics Inc., pers. commun.). Unless the range on the VHF transmitter can be significantly improved, future investigators might consider removing them from the unit to lighten the PTT. Elimination of the VHF unit would lighten the PTT by approximately 75 g. The C-cell batteries could be replaced by D-cell batteries which theoretically should increase the life span of the PTT, but would result in an increase in weight of approximately 100 g (W.P. Burger, Telonics Inc., pers. commun.).

PTTs in 1992 cost $3,500 (U.S.)/unit and can be refurbished for approximately $800/unit. Data processing costs from Service Argos are based on the equivalent of a PTT transmitting one to six times each day for one year (PTT-year). Each PTT-year (1992) costs $4,000 and the fee for special animal process costs an additional $1.50/day/PTT. Each conventional VHF radio collar costs $330/unit and has a life span of approximately three years. We assumed each wolf pack would contain a minimum of three collars; one PTT and two VHF collars for the PTT-equipped pack and three conventional collars for the VHF-equipped pack. We assumed each PTT-equipped pack would be visually observed six times/year to collect data on productivity, den site locations, mortality; only standard normal processing would be used (requires 0.5 PTT-year of data processing); and each PTT would transmit six hours every two days for six months or longer (requires one recapture per year). We also assumed a study duration of three years, capture costs of $1,000/individual, and one hour of fixed-wing aircraft charter ($140/hour) per relocation for VHF equipped packs (W.B. Ballard, unpubl. data). Using the above assumptions, the average annual cost to maintain a PTT and two VHF transmitters in a wolf pack over a three-year period was $7,327. Assuming the PTT transmitted an average of six months and provided an average of 28 relocations/month (168 locations), the average cost/relocation was $44. To attain the same number of relocations with conventional VHF telemetry each relocation would cost about $148. Assuming a more realistic monitoring intensity of once/week, the average annual cost/relocation was $166.

Cost per relocation was cheaper for both methods when a greater number of relocations were obtained per year. For an average wolf study lasting three years and requiring 50 relocations per year, costs per relocation were $147 and $172 for PTT and VHF transmitter equipped packs, respectively. Differences between the two methods increased as the total numbers of relocations/year increased. At 200 relocations/year average cost/relocation was $37 and $147, respectively, whereas for 400 locations average cost was $22 and $144, respectively. Reasons for these large differences include high initial costs for wolf PTTs but subsequently low monitoring costs in comparison to low initial costs for conventional VHF transmitters, but relatively high fixed monitoring costs (one hour charter aircraft/relocation). Clearly, use of satellite telemetry is cost-effective for obtaining large quantities of movement and relocation data, and may also provide indications of activity patterns once additional effort has been made to calibrate and categorize such data (Fancy and Ballard this volume).

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