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A CRITIQUE OF WILDLIFE RADIO-TRACKING AND ITS USE IN NATIONAL PARKS

A REPORT TO THE U.S. NATIONAL PARK SERVICE

by L. David Mech and Shannon M. Barber

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SUMMARY

Because of the naturalness of National Parks and because of the public's strong interest in the parks, the National Park Service (NPS) must gather as much information as needed to help understand and preserve the natural functioning of its ecosystems, and especially of its wildlife. The most useful technique for studying wildlife is radio-tracking, or wildlife telemetry. Radio-tracking is the technique of determining information about an animal through the use of radio signals from or to a device carried by the animal.

The basic components of a traditional radio-tracking system are (1) a transmitting subsystem consisting of a radio transmitter, a power source and a propagating antenna, and (2) a receiving subsystem including a "pick-up" antenna, a signal receiver with reception indicator (speaker and/or display) and a power source. Most radio tracking systems involve transmitters tuned to different frequencies (analogous to different AM/FM radio stations) that allow individual identification.

Three distinct types of radio-tracking are in use today: (1)conventional, very-high-frequency (VHF) radio tracking, (2) satellite tracking, and (3) Global Positioning System (GPS) tracking. VHF radio-tracking is the standard technique that has been in use since 1963.

However, radio-tracking can be considered intrusive in that it requires live-capturing animals and attaching a collar or other device to them. A person must then monitor signals from the device, thus usually requiring people in the field in vehicles, aircraft, and on foot. Nevertheless, most national parks have recognized the benefits of radio-tracking and have hosted radio-tracking studies for many years; in some parks, hundreds of animals have been, or are being, so studied.

As a result, some NPS staff are concerned about actual or potential intrusiveness of radio-tracking. Ideally, wildlife studies would still be done but with no intrusion on animals or conflict with park visitors.

Thus the NPS has decided to closely examine the technique and use of radio-tracking to determine (1) if any less-intrusive method could supply the same information, (2) what the full range of radio-tracking technology is, to determine if the least-intrusive techniques are being used, and (3) whether future technological improvements might lead to less-intrusive techniques. The present review is the result.

We first present a simple overview of radio-tracking technology, its benefits, variety, cost, and availability, advantages and disadvantages, and recent refinements that, if used, could reduce research intrusiveness. Then we consider whether any less-intrusive, non-radio-tracking techniques could supply the same information. Next we discuss possible future improvements and suggest some that would help reduce intrusion during wildlife research in national parks.

Last, we review radio-tracking technology in detail for readers who want a more complete understanding. This review should also allow administrators and scientists to determine whether the least-intrusive radio-tracking techniques are currently being used.

We conclude that no substitute for radio-tracking appears to be on the horizon but that a few recent improvements in the technology can reduce some of its intrusiveness. Further, we recommend that the NPS (1) formally assess the extent of park visitors' perceptions and concerns about any intrusiveness caused by wildlife radio-tracking studies (2) help minimize

visitor concern about the technique by educating the public about radio-tracking and some of its findings in the parks, (3) promote use of the most up-to-date refinements and improvements in radio-tracking technology, and (4) encourage funding projects using such technology.

INTRODUCTION

The U.S. national park system has long been one of the most important, if not <u>the</u> most important, venues for environmental research in the world. This fact pertains especially for wildlife research, and many prominent wildlife studies have been conducted in the parks (Murie 1941, Mech 1966, Houston 1982, Peterson 1977, Mech et al. 1998), including such classics as those of Murie (1944) on wolves and Craighead and Craighead (1972) on grizzly bears.

The reason so much wildlife research has been conducted in the U.S. national parks is obvious - the national park system forms the most extensive tract of pristine wild land anywhere, with animal populations functioning essentially unhindered by human activities. In other words, the parks and their wildlife are natural.

The same reasons that have drawn scientists to the national parks also daily attract multitudes of private citizens there. In some cases, park wildlife studies themselves have put national parks on the map (Murie 1944, Allen and Mech 1963) and have caused increased visitation.

Both because of the intrinsic value of the parks' naturalness and because of the public's strong interest in the national parks, the National Park Service (NPS) is mandated to gather as much information as needed to help understand and preserve the natural functioning of its ecosystems, especially its wildlife.

It is inevitable that the administrative infrastructure that helps preserve the system yet helps host millions of visitors will also impose on the visitor. Thus park visitors must tolerate entrance fees, concessions, park personnel, laws, rules, regulations, and various restrictions. As public visitation increases, such impositions will also increase.

Park ecosystems are complex, and in order to meet its mandate to preserve them, the NPS needs to understand them. Understanding natural ecosystems requires research. Increased park use further fosters the need for increased information to help preserve park resources, manage the visitation, and minimize the conflicts among the natural system, the administrative infrastructure, and the constituents.

RESEARCH IN NATIONAL PARKS

Research in national parks forms both part of the solution to contending with the above conflicts and part of the problem. The information that research provides greatly facilitates administration and management of park resources. For example, public use surveys provide administrators with information on the number of facilities necessary, and their best locations. Nevertheless, the surveys intrude on visitors' park experience.

So, too, it is with wildlife research. Wildlife research in national parks has more potential to be both problem and solution than does most research. This is because wildlife species form one of the most important reasons people visit parks and because wildlife constitutes one of the most contentious park resources. Bears versus people, proper bison management, and elk population control have all been longstanding problems for National Park Service (NPS) administrators. Wolf reintroduction to Yellowstone was contentious for decades before adoption, and wolf management will continue to be contentious long after full restoration.

Thus wildlife research plays a special role in national park administration, and it is imperative that the best possible information about wildlife in the parks be developed. Decades ago, that meant merely a lone naturalist with binoculars, snowshoes, and a notepad, blending into the environment like every other one of the meager numbers of park visitors. Today, as visitor loads have mushroomed and potential conflicts multiplied, wildlife research means technology. No number of naturalists with notepads will ever be able to assess the details of the effects of wolves on Yellowstone's elk population.

With increased use of improved technology for wildlife research comes the potential both for much better understanding of wildlife problems and for greater conflict with visitor appreciation of the parks. The use of aircraft to census wildlife is an obvious example.

WILDLIFE RADIO TRACKING

The technique that has most revolutionized wildlife research, however, is radio-tracking, or wildlife telemetry. As we will discuss, the potential for learning new information with this technique is almost unlimited. On the other hand, the technique requires the live-capture of animals and usually the attachment of a collar or other device to them. It then usually requires someone to listen for a signal from the device periodically. This means people in the field in vehicles, aircraft, and on foot.

Despite the disturbance caused by radio-tracking wildlife, most national parks have recognized the benefits of the technique and hosted radio-tracking studies for many years; in some parks, hundreds of animals have been, or are, being studied, by radio-tracking. Consequently, some NPS staff have voiced concern about the actual or potential intrusiveness of radio-tracking studies. Ideally, such studies would still be done but with no intrusion or conflict with visitors.

The Present Review

Thus the NPS has sought to closely examine the wildlife radio-tracking technique so as to determine (1) if any less-intrusive methods could supply the same information, (2) what the full range of radio-tracking technology is in order to determine if the least-intrusive techniques are being used, and (3) whether future technological improvements might lead to less-intrusive techniques. The present review is the result.

Our approach will be to first present a simple overview of radio-tracking technology so the reader will be aware of the benefits, variety, cost, and availability of the technology, and the advantages and disadvantage of each type. We will also highlight the little-known, recent refinements that, if used, could reduce research intrusiveness.

Then we will examine the question of whether or when any less intrusive, non-radio-tracking techniques could supply the same information. Next we will discuss what future improvements may be on the horizon and suggest some that, if or when doable, would help reduce intrusion in national parks.

Last, we will present a detailed review of radio-tracking technology for readers who want a more complete understanding of the technique in question. This review will also allow administrators and scientists to determine whether the least-intrusive radio-tracking techniques are being used.

Overview of the Radio-tracking Technique

Radio-tracking is the technique of determining information about an animal through the use of radio signals from or to a device carried by the animal. “Telemetry” is the transmission of information through the atmosphere usually by radio waves, so radio-tracking involves telemetry, and there is much overlap between the two concepts.

The basic components of a radio-tracking system are (1) a transmitting subsystem consisting of a radio transmitter, a power source and a propagating antenna, and (2) a receiving subsystem including a “pick-up” antenna, a signal receiver with reception indicator (speaker and/or display) and a power source. Most radio tracking systems involve transmitters tuned to different frequencies (analogous to different AM/FM radio stations) that allow individual identification.

Three distinct types of radio-tracking are in use today: (1) very high frequency (VHF) radio tracking, (2) satellite tracking, and (3) Global Positioning System (GPS) tracking. VHF radio-tracking is the standard technique in use since 1963. An animal wearing a VHF transmitter can be tracked by a person on the ground or in the air with a special receiver and directional antenna.

Briefly, the advantages of VHF tracking are relatively low cost, reasonable accuracy for most purposes, and long life; disadvantages are that it is labor-intensive and can be weather-dependent if aircraft-based. Nevertheless, VHF radio-tracking is by far the most useful and versatile type of radio-tracking, for not only does it yield location data, but it also allows investigators to gather a variety of other types of information (Mech 1974, 1980, 1983).

Satellite tracking employs a much higher-powered transmitter attached to an animal. The signal is received by satellites and the animal's calculated location is sent to a researcher's computer. Satellite tracking requires a much higher initial cost and is much less accurate (mean accuracy = 480 meters [Fancy et al. 1989]) and, for most species, is shorter-lived than VHF systems.

If only animal locations and gross movements are of interest to a study, such as a dispersal path, satellite tracking is advantageous because it requires no personnel in the field once the tracking device is placed on the animal. It is especially useful for monitoring long-range movements. However, most wildlife studies also require a variety of other information that satellite tracking does not provide, including number of companions, individual productivity, behavior, and population size and trend. For carnivores, information about predatory habits, such as rates, location, species, age, sex, and condition of their kills, cannot be obtained by satellite tracking.

GPS tracking is based on a radio receiver (rather than a transmitter) in an animal's collar. The receiver picks up signals from a special set of satellites and uses an attached computer to calculate and store the animal's locations periodically (e.g. once/15 minutes, once per hour, etc.). Depending on collar weight, some GPS collars store the data and drop off the animal when expired to allow data retrieval; others transmit the data to another set of satellites that relay it to the researchers; and still others send the data on a programmed schedule (e.g., daily) to biologists who must be in the field to receive them.

GPS tracking also has high initial costs and at present is relatively short-lived and applicable to mammals the size of a wolf or larger, or to birds on which solar cells can be used. GPS tracking is highly accurate and especially suited to studies where intensive and frequent data many locations/day) are needed or useful. Depending on several variables, GPS tracking may or may not require frequent field visits.

Recent Refinements in Radio-tracking

Three recent refinements in radio-tracking can reduce intrusiveness by researchers using the technique. The first is the ability to program radio-collars to transmit only at certain times ("duty cycling") rather than continually. This refinement can double or triple transmitter life, thus reducing or eliminating the need to recapture an animal for replacing an expired collar. For example, using duty cycling, batteries in elk collars could now last 8 years or more.

The second recent refinement is a reduction in weight of GPS collars, thus allowing them to be used on smaller species. Or by adding additional batteries to the reduced package, larger animals could be tracked longer.

Third, GPS transmitters powered by solar cells are now available for birds. This new availability will allow biologists to study many birds without having to venture into the field to determine each location.

Details about these three refinements can be found below in the detailed radio-tracking section.

Potential Substitutes for Radio Tracking

The radio-tracking technique is so revolutionary (Mech 1983) that there is no other wildlife research technique that comes close to approximating its many benefits. For example, before radio-tracking, the study of animal movements depended on live-trapping and tagging animals and then hoping to recapture them somewhere else. A refinement was the use of visual markers such as color-coded collars that allowed observers to identify individuals from afar. The crudeness and biases inherent in this method are obvious, but the technique is the next best to radio-tracking for this kind of study.

Although new technology and scientist ingenuity do occasionally produce other new wildlife research techniques, none have come close to substituting for radio-tracking. Two new techniques bear mentioning because they are being much touted for their lack of invasiveness. They are the use of hairs plucked from free-ranging animals, and the use of scats, both for DNA analyses. Both techniques may be highly useful, but such use would only be for very specialized objectives. Both can tell presence/absence of a species and even minimum numbers present, and scat analyses may even yield a reasonably accurate population estimate (Kohn et al. 1999). However, doubts and cautions about the research promise of these non-invasive DNA techniques are still being aired (Taberlet et al. 1999, Garshelis 2001).

Population estimates of wolves are usually done by VHF radio-tracking and aerial observation. Therefore, conceivably if the sole or primary objective of a wolf radio-tracking project is to estimate the population, DNA analysis of scats could be a substitute. However, this technique has not been proven practical yet with wolves, although it is currently under study (Peterson, Mech, Vucetich, and Wayne in progress).

Although the scat analysis technique for censusing would be much less intrusive than radio-tracking, there are three major disadvantages: (1) the logistics of proper wolf scat collection for a population estimate throughout the area to be censused are highly challenging and would require considerable field effort, (2) lab analyses of scat-derived DNA are problematic (Taberlet et al. 1999). and (3) the scat technique would provide little of the complementary data that radio-tracking yields such as behavioral observations, mortality rates and causes, dispersal, and various other data depending on the amount and frequency of tracking time.

Improvements Needed in Radio-tracking Systems

One of the most important improvements that could be made for all types of radio-tracking would be more efficient power sources, i.e. lighter, smaller batteries. This advance would allow any or all of the following: (1) longer life, (2) greater range, (3) lighter packages,

(4) use of present radio-tracking devices on smaller animals. Such improvements would greatly facilitate VHF, satellite and GPS radio-tracking.

More efficient batteries that would prolong transmitter life, of course, would have to be accompanied by longer-lives of the other transmitter components. Although this is not a problem for periods of up to 4 years, it could become a problem if batteries allowed even longer life.

Most of the above advances would also translate into reduced intrusiveness through reduced live-trapping for re-collaring, or reduced in-field tracking. For example, for a given weight of a GPS collar, longer life would mean either a higher rate of location acquisition or a longer period of data collection. These advantages would allow more species to be tracked with GPS collars rather than VHF collars, thus reducing the need for in-field tracking time by biologists.

A second improvement would be a more efficient transmitting antenna. A more efficient antenna would reduce power requirements, thus translating to gains and advantages similar to those of a more powerful battery.

More efficient and longer-lived and more durable solar cells would be a third advance that could translate into less intrusiveness in radio-tracking. Currently, solar cells are useful in certain applications, especially with birds. However, with mammals, cells can be covered by fur, mud and debris. Longer-lived rechargeable batteries, which act as buffers for storing energy from solar cells, would allow longer total life of solar-powered transmitter packages. Thus they would also constitute a significant improvement.

Greater accuracy of satellite tracking would render this technique far more useable for wildlife research within national parks. Lower costs of satellite and GPS equipment would allow biologists to make greater use of those technologies rather than the more intrusive VHF tracking, at least for the specialized objectives they can help meet.

Prospects for Improvements to Reduce Intrusiveness of Radio-tracking

Neither leading electronics engineers in the wildlife radio-tracking field nor National Aeronautical and Space Administration (NASA) personnel consulted for this report have indicated that any technological breakthroughs are imminent that will revolutionize wildlife radio-tracking. Thus only incremental improvements can be expected for the foreseeable future.

Perhaps the next improvement will be the perfection of hydrogen fuel cells small enough to be used in animal radio-transmitters; theoretically they could yield longer life or lighter packages. A current estimate is that such cells might be available in 3-5 years (Hulbert 2001).

If satellite telemetry could be made far more accurate, it could at least save on personnel-days in the field in vehicles, on foot, or in the air. However, prospects are low for increased satellite-tracking accuracy soon. Consultation with manufacturers of satellite telemetry equipment confirms that the relatively low degree of accuracy of satellite systems is inherent in the basic position-finding methods used.

Of course, radio-tracking technology, like all other technology, will continue to improve with time, and costs will decrease. The high degree of competition among the many commercial companies (Appendix A) providing radio-tracking equipment guarantees that. However, even if all the improvements suggested above were made, they would only reduce, not eliminate, the basic intrusiveness of radio-tracking. Animals would still need to be caught, and they would still need to host transmitter packages, external or internal.

Therefore, the most that can be expected in the near term for minimizing intrusiveness of wildlife radio-tracking is for researchers to make use of the best, most appropriate, radio-tracking technology they can for reaching their objectives. Because that approach is already in the best interests of wildlife studies, most scientists are already using it.

However, improvements in technology are occurring rapidly, so some biologists may not be aware of them. Thus it is useful to review the radio-tracking technique and its latest improvements in more detail.

DETAILS OF RADIO-TRACKING TECHNOLOGY

The following detailed look at the technique of wildlife radio-tracking is provided to familiarize administrators and biologists with the current state of the technique. This greater awareness should facilitate an understanding of any problems caused by radio-tracking and should help researchers choose the most effective and least intrusive equipment and techniques.

Radio-tracking brought two new advantages to wildlife research: the ability to identify individual animals and the ability to locate each animal when desired. These advantages have led to the wide application of radio-tracking since the first complete workable system was designed (Cochran and Lord 1963). Radio-tracking has been used to study animals as varied as snakes, crayfish, dolphins, tigers, and elephants and in most major countries.

In addition to more straightforward applications such as movement/home range analysis and mortality studies, radiotelemetry has proved useful in examining many diverse topics including disease transmission (Cheeseman and Mallinson 1980), scent marking (Peters and Mech 1975; Charles-Dominique 1977), predation and co-evolution (Mech 1967, 1980), vocalizations (Harrington and Mech 1979; Gautier 1980; Alkon and Cohen 1986), socioecology and breeding behaviors (Mech 1980), sleep characteristics (Schmidt et al. 1989), physiological studies of heart rate, respiration rate, body temperature (Kreeger et al. 1990), and nest egg condition (Howey et al. 1977, 1987; Schwartz et al. 1977; Boone and Mesecar 1989).

Advances in radio-tracking since Cochran and Lord's first system include refinements of conventional, or very high frequency (VHF), telemetry as well as entirely new systems such as satellite telemetry and GPS radio-tracking. Improvements in conventional VHF telemetry now enable researchers to determine, for examples, whether an animal is active (feeding, walking, running) or resting, and the time spent in mortality from death until the transmitter is recovered. Microphone-containing transmitters allow researchers to listen to a creature's vocalizations and ambient sounds (W. W. Cochran, personal communication).

Satellite telemetry uses satellites to relay the animal's location signal (sent by the telemetry package attached to the animal) to other receiving stations for interpretation. This allows researchers to track far-ranging animals such as some marine mammals that previously were too difficult to track using the relatively shorter range of the conventional VHF system.

GPS radio-tracking --in which the telemetry package attached to the animal receives information from three or more satellites to determine an animal's location–is used to store location data in the telemetry unit for later retrieval or remote downloading. This gives researchers greater location accuracy and decreases invasiveness to animals when compared with VHF telemetry.

Conventional VHF Radio-tracking

Conventional VHF radio-tracking systems consist of transmitting and receiving systems.

Transmitting Systems

Basic transmitting systems include a transmitter, power supply, transmitting antenna, and material to protect the electronic components and other material to attach the system to the animal. The size and mass of the total transmitting package, type and strength of signal sent, and life of the unit vary considerably.

Transmitters. Each radio transmitter consists of electronic parts and circuitry, usually including a quartz crystal tuned to a specific frequency. Crystals come in different degrees of shock-resistance, and for animals such as wolves that lead aggressive lifestyles, high-shock resistant crystals are usually used.

Signals can be either continuous, which sounds through a speaker like a high-pitched whine, or pulsed, which sounds like a series of "beeps." Pulsed signals are usually used at rates of 30-120 per minute. Lower pulse rates yield longer transmitter life. Pulse widths can also vary, with 18 milliseconds being the minimum that is easily tracked. The narrower the pulse, the longer the life.

Transmitting Frequency. Frequencies used in wildlife telemetry usually range from 27 MHz to 401 MHz. VHF transmitters typically give a ground-to-ground range of 5-10 km which is increased to 15-25 km when received aerially (Rodgers et al. 1996). Lower frequencies propagate farther than higher frequencies since they reflect less when traveling through dense vegetation or varying terrain (Cederlund et al.1979; Mech 1983). However, lower-frequency signals (e.g., 32 MHz) consist of longer wavelengths, which increase the size of the transmitting and receiving antennas necessary for detecting them.. This has implications for feasibility and receiver portability (see below).

The commonest frequency ranges used for VHF tracking are 148-152 MHz, 163-165 MHz, and 216-220 MHz. The higher frequencies bounce more (e.g. off mountains) but have the advantage of requiring smaller antennas. Whatever frequency is selected, individual transmitters are usually tuned $\geq$ 10 KHz apart to allow distinctiveness despite signal drift (1-2 KHz) due to temperature and battery fluctuations (Mech 1983).

Frequency selection is regulated by law in the United States (by the Federal Communications Commission, FCC) and internationally as well. Thus authorization is necessary from local and federal agencies to avoid operating at prohibited frequencies.

An additional frequency-choice consideration involves proximity of other research projects using similar frequencies. Coordination among projects is necessary in order to avoid duplicating frequencies for individual study animals that may use the same areas. One famous example highlighting the importance of this consideration involved a radio-tracker homing in on what he thought was an elk. Upon closing in on the animal, he discovered that it was some other researcher's grizzly bear!

Power Supply. Complete transmitter packages can weigh as little as 0.8 g (Samuel and Fuller 1996). However, many transmitter packages weigh much more, with the principal weight determined by the battery used and the collar and protective material. Since both the total weight and the life of the transmitter are determined by the battery, its selection is critical. Clearly, there are species-specific limits to the weight an animal can carry as a transmitter package without significantly affecting its survival or behavior. Therefore, a compromise must be made by using batteries heavy enough to meet the study objectives but light enough to minimize effect on the animal.

Lithium batteries (2.9 – 3.9 V) are generally employed in conventional systems because they have longer shelf life and an energy capacity-to-volume ratio twice that of mercury or silver oxide batteries. Silver oxide batteries are often used with subcutaneous transmitters to minimize bulk. However, these transmitters usually only last 6-120 days. (Although zinc-air batteries have about the same energy density as lithium batteries, they are not widely applicable in wildlife telemetry because they can only be used in situations where dirt or moisture will not enter the required vent hole [Samuel and Fuller 1996]).

Photovoltaic or solar cells have also been utilized in transmitter packages (Aucouturier et al. 1977; Snyder et al. 1989). These cells theoretically allow indefinite signal output until other components of the transmitter fail. However, the signal is only transmitted during daylight when using solar cells alone. Attempts to achieve round-the-clock signal transmission while extending battery life have included the combined use of solar cells and rechargeable batteries. During the day, the transmitter pack uses the solar battery to operate and to store additional energy in the NiCd rechargeable batteries. At night, the unit is powered solely by the NiCd battery. While this system initially allows round-the-clock signal output, eventually the signal would only be broadcast during the day since rechargeable batteries can only be recharged a limited number of times.

Another recent advance in VHF telemetry which extends battery life is duty-cycling which allows the transmitter to turn on and off at regular intervals (e.g., on 8 hr, off 16 hr). This feature minimizes the number of times a radio-tagged animal must be recaptured to replace a dead battery.

Transmitter Protection.. Transmitters are usually coated with “potting”, a resin-like material used to seal the electronic components. Transmitter packages are coated to minimize damage done both by the animal (chewing, scratching, etc.) and by the environment (moisture, mechanical damage, etc.) to the sensitive circuitry. The most common reason for transmitter failure is a dysfunctional battery attributed to moisture exposure or shelf deterioration (MacDonald 1978).

Many types of coating are commercially available such as beeswax, dental acrylic, epoxy resin, electrical resin, silastic, and Plasti-Dip (Mech et al. 1965; Macdonald 1978; Donaldson 1980; Jansen 1982; Kuechle 1982). Transmitting units can also be hermetically sealed (Tomkiewicz 1996). Particular sealants provide specific advantages for different situations. Selecting the appropriate sealant is especially important when working with aquatic organisms. Morris (1992b) described a method of waterproofing transmitter packages for depths up to approximately 100m.

Transmitting Antennas. Transmitting antennas are critical components of radio-transmitter packages since they project the signal for capture by receiving antennas. Along with power supply, the antenna’s orientation, construction, and length determine the effective power radiated (EPR), and therefore, the range at which the signal can be received. Ideally, antennas should be oriented perpendicular and away from the animal’s body. However, such antennas become entangled in vegetation, break off or are torn off. Thus often they are embedded between layers of a collar, thus protecting them but compromising their range.

Two basic types of transmitting antennas are whip antennas and loop antennas. Whip antennas consist of a wire with one free end and the other end attached to the transmitter. The antenna’s entry point must be thoroughly sealed to prevent moisture damage to the transmitter. Whip antennas are usually shorter than the ideal length, so sometimes they include additional components to help compensate for this decrease in EPR (Kenward 1987:32). An additional decrease in EPR is due to the whip antenna’s close contact with the animal’s body (Cochran 1980).

While whip antennas incorporated into a collar are often used on large mammals, simple loop antennas (connected on both ends to the transmitter) are usually used on small mammals (Anderka 1987). Loop antennas consist of copper, brass, or coated wire which fits around the animal's neck. The diameter of the loop is adjusted to tune the antenna to match the frequency of the transmitter. Therefore, if the loop collars are tuned prior to use on an animal, the diameter must not be altered. Otherwise, the loop collars can be tuned in the field when placed on an animal.

Transmitter-Attachment Methods. Mech et al. (1965) suggested five guidelines in selecting the ideal transmitter package and attachment for a particular project: 1) minimum weight, 2) minimum effect on the animal, 3) maximum protection for the transmitter, 4) permanence of the attachment, and 5) maximum protection of transmitter from animal mortality factors such as predation and accident. Various attachment methods show varying effects on animals (Garrott et al. 1985; Marcstrom et al. 1989) (see below).

Radio-Tagging Mammals. Collars have traditionally been used to fit transmitter packages on mammals (Pouliquen et al. 1990) with prominent necks, large ears, or horns/antlers since these structures help prevent the collar from slipping over and off the head of the animal. Standard collars cannot be used with animals such as boars (Jullien et al. 1990), which have temporarily enlarged necks during the rutting season, and polar bears (Anderka and Angehrn 1992), which undergo large seasonal weight changes. Jullien et al. (1990) used an expandable collar to allow for seasonal neck circumference changes in the boar, while Kolz et al. (1980) fitted polar bears with a loose collar attached to a secure back harness. Because the necks of male ungulates swell during the rut, researchers apply foam rubber inside the collars to allow for the swelling.

Expandable collars allowing for growth of young animals have also been applied successfully to mountain lions (Garcelon 1977), bobcats (Jackson et al. 1985), pronghorns (Beale and Smith 1973), black bears (Strathearn et al. 1984), caribou calves (Adams et al. 1995), elk calves (Singer et al. 1997), white-tailed deer fawns (Kunkel and Mech 1994), and coyotes. These collars remain securely fitted on the animal as sewn pleats or foam-rubber inserts give way with the growth of the animal. Break-away collars, in contrast, are designed to fall off the animal following degradation of weaker materials purposely incorporated into the collar. Break-away collars with cotton fabric have been used on black bears (Hellgren et al. 1988), while rubber or wire breakaway components have been used on sea otter collars (Loughlin 1980).

Some mammals do not retain collars well since they do not have prominent necks. For example, mammals such as hedgehogs (Morris 1966), badgers (Kruuk 1978; Cheeseman and Mallinson 1980), dolphins (Jennings and Gandy 1980), and harbor seals (Broekhuizen et al. 1980) have instead been fitted with backpack harnesses. Tail harnesses have also been used to fit animals with short stocky necks such as manatees (Priede and French 1991).

Some alternatives to applying collars or harnesses on mammals include ear-tag transmitters (Servheen et al. 1981), transmitters fixed with adhesive directly onto the mammal such as bats (Stebbings 1982) or bears (Anderka 1987), and transmitters making use of an animal's special structures. One study embedded a transmitter into the horn of the black rhinoceros with a loop antenna fastened around the base of the horn (Anderson and Hitchins, 1971).

The above alternatives are not appropriate for highly social animals such as wolves. Instead, very rugged or sometimes even armored collars must be used since extensive grooming and collar chewing occurred that can result in damage or removal of the transmitter, antenna, or entire collar (Thiel and Fritts 1983).

Surgically implanted transmitters such as subcutaneous transmitters, abdominal transmitters, or rumen transmitters represent other attachment alternatives. Transmitters have been implanted in mammals such as beavers (Guynn et al. 1987), river otters (Melquist and Hornocker 1979; Davis et al. 1984), sea otters (Garshelis and Siniff 1983; Williams and Siniff 1983; Ralls et al.1989), yellow-bellied marmots (Van Vuren 1989), lions (McKenzie et al. 1990); grizzly bears (Philo et al. 1981), and black bears (Jessup and Koch 1984).

Two considerations when using implanted transmitters are greatly reduced signal range (sometimes < 50%; Samuel and Fuller 1996) and increased invasiveness to the animal that may result in greater data bias and potentially require subsequent veterinary procedures (Morris 1980). See below for assessment of effects of implanted transmitters.

Radio-Tagging Birds. Attachment methods for fitting transmitters to birds vary widely. Examples include transmitters with whip antennas fitted to backpacks with attachment loops under the wings (Dwyer 1972, Hardy 1977); loops meeting near the breast (Amlaner et al. 1978), or loops under the legs (Rappole and Tipton 1991); loop-antenna harness-chest packs (Nicholls and Warner 1968; Siegfried et al. 1977); whip antennas adhered directly to tail feathers (Dunstan 1973; Kenward 1976, 1978; Raim 1978; Giroux et al. 1990); collars, neck band mounts, or necklaces (Amstrup 1980; Shields and Mueller 1983; Montgomery 1985; Marcstrom et al. 1989); leg-band transmitters (Melvin et al. 1983).

Other methods include suture-only attachments (Martin and Bider 1978; Mauser and Jarvis 1991); adhesive-only attachments (Jackson et al. 1977; Raim 1978; Harrison and Stoneburner 1981; Perry 1981; Perry et al. 1981; Heath 1987; O'Conner et al. 1987; Wanless et al. 1989; Wilson and Wilson 1989; Sykes et al. 1990; Johnson et al. 1991); suture and adhesive attachments (Wheeler 1991); patagial band mounts; and surgical implants (Klugman and Fuller 1990; Anderka and Angehrn 1992; Olsen et al. 1992).

Radio-Tagging Other Animals. Other animals such as reptiles, amphibians, and fish have also been radio-tagged. Sea turtles, for example, have been tracked using transmitting harnesses (Ireland 1980). Snakes have been fitted with internal transmitters that still allow the snake to move through small openings and to shed its skin (Speake et al. 1979; Anderka and Weatherhead 1983; Weatherhead and Anderka 1984). Ingested implants have also been used in snakes (Lutterschmidt and Reinert 1990). Transmitters have been surgically implanted in endangered hellbenders (Stouffer et al. 1983) and amphibians such as toads (Smits 1984). Both internal and external radio-tags have been applied to fish as well (Haynes and Gray 1979). Different tags, or a combination of tags, must be utilized when considering freshwater vs. mixed or salt water because of the differences in signal propagation due to varying degrees of conductivity (Priede 1992).

Other Uses Of Transmitters In Wildlife Research. Transmitters have been used for a variety of special purposes beyond individually marking and tracking animals. Some have been placed in tranquilizing darts to allow researchers to track darted animals until they succumb to the drugs (Lovett and Hill 1977).

Radio signals have been employed with special capture collars (Mech et al. 1984; Chapman et al. 1985a, 1985b; DelGiudice et al. 1990; Mech et al. 1990; Kunkel et al. 1991;

Mech and Gese 1992). Upon receiving the activating signal, the collar injects the drug contents of a dart into the animal's neck. Should the dart fail or not provide sufficient drug, the researcher can address the collar again – this time to release the contents of a second (back-up) dart into the animal. Transmitter-fitted anesthetic darts have also been placed in penguin nests for remote activation to capture the birds (Wilson and Wilson 1989).

Transmitters have also been used both to monitor trap status and also to remotely activate a release system on traps (Hayes 1982; Nolan et al. 1984). Transmitters have served to mark important locations (Nicholls et al. 1981). For example, before hand-held GPS units were available, researchers doing aerial surveys marked wolf kill-sites by dropping a transmitter protected by sponge rubber; then later, using a portable hand-held receiving system, they could hike to the site for further investigation. Transmitters have also been attached to prey that may be taken to dens or nests, allowing scientists to find the den or nest (Samuel and Fuller 1996). Implanted transmitters can also help lead authorities to poachers (Samuel and Fuller 1996).

Researchers have used vaginal transmitters in female deer to mark fawning sites (Bowman and Jacobson 1998). These transmitters emit a changed pulse when expelled from the doe (expected during fawning) because they are temperature-sensitive. Researchers can then home in (see Tracking Methods) on the transmitter and find the fawn nearby.

Receiving Systems

Receiving systems detect and identify signals from transmitters. A basic receiving system consists of a battery-powered receiver, a receiving antenna, cables, a mechanical or human recorder, and a human interpreter with accessories such as a speaker or headphones (useful for reducing external noise when detecting the transmitted signal, Mech 1983; Samuel and Fuller 1996). Other accessories include devices for mounting receiving antennas to vehicles and aircraft, scanners to enhance searching for numerous signals, specialized recorders to aid in data collection, downloading and data-interpreting devices, and various types of software.

Receivers. Receivers must be able to detect and distinguish signals of specific frequencies. Standard receiver controls include a three-position power switch (internal or external power and off), dials for gain and channel, band, and fine frequency adjustments, jacks for an external antenna (UHF or BNC), headphones, a recorder, and external power. Some receivers also have a volume control. Volume differs from gain in that an increase in gain increases signal sensitivity (up to a point beyond which the sensitivity does not increase) whereas increasing volume affords no greater signal sensitivity (Mech 1983).

Some receivers require frequencies to be entered by dials while others are digitally programmable. Many receivers also include two needle gauges; one indicates remaining battery power and the other the strength of the signal received. The latter can be especially useful in aerial tracking where the signal strength changes rapidly (Mech 1983). Most portable receivers are powered by standard alkaline batteries (i.e. 8 AA, 1.5 V penlight cells) (Cederlund et al. 1979) and will function for 8-12 hours. (With rechargeable batteries, the unit functions 5-8 hours [Samuel and Fuller 1996].) Generally, receiving units can also be powered externally from vehicle cigarette lighters or separate larger batteries such as motorcycle or marine batteries.

Some receivers include a sweep option that allows the unit to search within 10 KHz of the tuned signal. This is useful since signal drift can occur in the field due to temperature and battery fluctuations (Mech 1983). Other receivers are programmable with memory functions and can automatically scan for several frequencies at user-defined intervals from as little as ½ second to as long as 10 minutes (Samuel and Fuller 1996). The researcher presets the search time and can stop the scanning to home in (see Tracking Methods) on a particular signal (Kuechle 1982). This time-saving feature allows the researcher to locate many animals in a short time. Hand-held walkie-talkie-size receivers (weight 352 g) that can store up to 999 frequencies are now available.

Receiving Antennas. Frequency determines the size of receiving antennas. In general, the higher the frequency, the smaller the antenna. For example, a receiver tuned for 150 MHz (wavelength 2 m) with an accompanying ½ wavelength multi-element Yagi antenna (see below) is available as a 1-m, hand-held unit, while a receiver tuned for 27 MHz (wavelength 11 m) necessitates a ½ wavelength multi-element Yagi antenna much larger (5.5 m) and thus is not practical as a hand-held device (Cederlund et al. 1979) (unless a loop antenna is used; see below).

Antennas serve to both increase the gain (signal gathering capacity) of a receiver and to assist the operator in determining the direction from which a signal is coming. Larger antennas (lower frequencies) generally yield greater gain and directionality but at the expense of portability. Selection of the appropriate antenna is important since even under ideal situations, half of the signal's power captured by the antenna is actually delivered to the receiver while the other half is re-radiated (Samuel and Fuller 1996).

The signal's power is transferred from the antenna to the receiver by coaxial cables which shield the electronic signal against extraneous noise and help minimize signal power loss (Samuel and Fuller 1996). If signal loss along the transmission line is too great, preamplifiers can be incorporated between the antenna and the transmission line (Kenward 1987; Howey et al. 1989).

The simplest kind of receiving antenna is a straight wire or "dipole" (one half the wavelength of the transmitted frequency) attached to the receiver's antenna jack. Dipole antennas are omni-directional and therefore, are most appropriate for presence /absence studies (Mech 1983). These antennas are often used at a stationary reception site in an automatic tracking system or as part of a portable unit mounted on vehicles (see Mounting Antennas).

Loop antennas can be a circle, an oval, or diamond-shaped, with, like other antennas, dimensions dictated by the signal frequency. Loop antennas are especially useful for minimizing the size of lower-frequency antennas so they can be used as hand-held portable units (Cederlund et al. 1979). Although loop antennas are bi-directional (the signal can be received equally strong from two different directions simultaneously), by merely moving a few hundred meters perpendicular to the bearings, and taking a second bearing, once can determine the direction of signal origin.

A more complicated antenna, the multi-element Yagi, is the most commonly used antenna in North America (Kuechle 1982). It consists of a horizontal length of metal (usually aluminum) with 3-17 vertical lengths attached to it, all in one plane. The length of the vertical elements and their spacing depend on signal frequency. Yagi antennas are directional with shorter elements at the distant end of the antenna. The signal's origin can be determined by swinging the antenna and determining the direction of the strongest signal when the tip of the Yagi (the shortest element) is farthest from the user (Mech 1983). Twin Yagi systems can be set up for greater range and more precise directionality. However that requires careful spacing of the antennas 1 or ¼ wavelength apart (Amlaner 1980; Anderka 1987).

Another type of receiving antenna is the Adcock, or 'H' antenna, often used for hand-held applications because it is smaller than the Yagi. However, this antenna has reduced gain and receives the signal equally strong from two directions, so the true direction of signal origin must be confirmed in the same way as with a loop antenna (Samuel and Fuller 1996).

Recent developments in hand-held receiving antennas include size and weight reductions and increased portability. Morris (1992a) described a copper antenna for 173 MHz that is appreciably smaller than the corresponding three-element Yagi but retains similar gain. Bosak (1992) illustrated a pocket-size receiver with two telescopic monopole antennas built into the casing. Extended, these monopoles form a dipole that has been used to track lizards. To detect underground lizards, one monopole from the receiver was stuck into a hole in the ground. For very short ranges, the system worked even when the monopoles were only extended 5-10 cm.

Bosak (1992) also described a flexible Yagi antenna with three, five, and ten elements constructed from flexible wire mounted on a nylon or kapron cord frame. The obvious plus to this antenna is its portability. The author stated that "When not in use the antenna is rolled up into a ball. If required in the field the antenna is stretched into a T-shaped frame lashed together from whatever material (e.g. flexible green twigs) is available locally" (Bosak 1992). A new precise method of close-up homing uses ultra high frequency antennas with short elements tuned to a transmitter's harmonic frequency to pinpoint a transmitter (Cochran and Pater 2001).

Mounting Antennas. Some radio telemetry projects require antennas too large to be hand-held. These antennas must be mounted either on stationary receiving stations or on portable vehicles such as an automobile. Stationary systems can be fixed (non-rotating) to record presence and absence data or rotated to determine the direction of the signal (Smith and Trevor-Deutsch 1980; Mech 1983). White and Garrott (1990) described ideal positioning for antennas mounted at stationary receiving stations for increased accuracy and coverage. Samuel and Fuller (1996) discussed the positioning of antennas with respect to vegetation, large buildings, obstructive terrain, etc. and its effect on the range of signal reception.

Mobile systems are especially useful for covering large ranges. When in heavily roaded areas, antennas mounted to vehicles can serve as presence/absence indicators (e.g. omni-directional antennas mounted with a magnet to the roof of a car) (Bray et al. 1975; Kolz and Johnson 1975; Mech 1983) or as direction-finding antennas (e.g. rotating stacked Yagi antennas attached to a compass inside the vehicle) (Cederlund and Lemnell 1980; Mech 1983; Hegdal and Gatz 1987).

Antennas mounted on aircraft generally consist of two Yagis or H types, one attached to each wing strut. The antennas can be positioned pointing forward or off to the side on either fixed-wing aircraft or helicopters (Whitehouse and Steven 1977; Gilmer et al. 1981; Inglis, 1981; Mech 1983).

Most aerial systems are set up with the antennas pointing to the side for fine-point location estimates when circling. Initially, the operator switches between the two antennas to determine coarse signal direction by finding the bearing where the signal from each antenna is equally strong, heads in that direction, and circles around the peak signal location to pinpoint the animal. This method of tracking is particularly useful for areas difficult to access by foot or automobile such as wilderness and remote mountainous areas. More complete descriptions of the process of aerial tracking can be found in Whitehouse and Steven (1977) and Mech (1983).

Recorders, Counters, And Decoders. Ultimately, a human is needed to interpret signals in wildlife studies. However, many automated devices can aid the researcher by performing a majority of the recording, counting, and decoding necessary for data analysis. These devices are very useful for presence/absence, activity, or physiological studies.

Recorders range from simple to complex. Kenward (1987) used a tape recorder to register transmitted signal pulses. Other devices such as a simple paper strip-chart recorder can register the presence or absence of signals in the receiving area of the antenna (Licht et al. 1989), along with time and date (Gillingham and Parker 1992). These recorders are especially useful for gathering physiological data (Kuechle et al. 1987; Althoff et al. 1989; Schmidt et al. 1989; Stohr 1989).

More complicated computerized systems can be programmed to scan for various signals, record their parameters, decode and process them for error and mean values, and store them for later retrieval (Howey et al. 1987; Janeau et al. 1987; Kuechle et al. 1989; Schober et al. 1989).

Counters and decoders are used in automatic recording systems primarily to count and decode signal pulses associated with physiological telemetry. These devices can receive signal pulses, measure their properties (i.e. amplitude, interval, etc.) and convert them into user-defined outputs (e.g. Schmidt et al. 1989 converted analog signals into digital signals to obtain EEG readings).

Tracking Methods

Researchers can track animals in the field through two main methods, homing in (either by ground or aerial tracking) and triangulating. Passive remote tracking is accomplished through automatic tracking systems (Cochran et al. 1965).

Homing. Homing consists of following a signal toward its greatest strength. As the researcher closes in on the animal, the signal increases and the receiver gain must be reduced to further discriminate the signal's direction. The process of proceeding forward and continually decreasing the gain is repeated until the researcher sees the animal or otherwise estimates its location when sufficiently near (Mech 1983). Homing can introduce bias to the data as the animal may be disturbed and behave differently as a result (White and Garrott 1990).

Triangulating. Triangulating involves obtaining two signal bearings from different locations (preferably at angles of about 90^o to one another) which then cross at the animal. In practice, it is better to take three or four bearings because antenna directionality is imprecise. When more than two bearings are plotted, the bearings form an error polygon on a map (Heezen and Tester 1967; White and Garrott 1990). This polygon theoretically contains the animal's location.

Significant error can be introduced if the bearings are not taken in a relatively short period, since the more time that passes, the greater the probability that the animal has moved. This problem can be avoided by researchers simultaneously taking bearings each from a different location. Triangulation locates an animal with minimal disturbance since the researcher can be far from the animal while obtaining a bearing. The farther away, however, the greater the error. Mech (1983) more completely describes the process of triangulation.

Automatic Tracking. Automatic radio-tracking differs from the above techniques because the researcher is not required to be in the field to obtain the animal's location. The obvious advantage is reduced human presence in the field. Also, since bearings are recorded automatically, measurements should be without subjective error (Angerbjorn and Becker 1992). A significant disadvantage to this method is the high initial investment in equipment and also its maintenance.

The first complete automatic radio-tracking system was the Cedar Creek (University of Minnesota) system (Cochran et al. 1965). This system recorded locations of 52 animals (reception range from approximately 100 m to 10 km) every 45 seconds through the use of two rotating stacked-Yagi antennas on 20-m and 30-m towers.

Since that pioneering system, other types of automatic tracking systems have been described (Angerbjorn and Becker 1992). Nicholas et al. (1992) have used an inexpensive, low-maintenance system that automatically records signals from free-ranging seals even if the signal is weak or the background noisy.

Satellite Tracking

Satellite telemetry utilizes a platform transmitter terminal (PTT) attached to an animal which sends an ultra high frequency (401.650 MHz) signal to satellites. The satellites calculate the animal's location based on the Doppler effect and relay this information to receiving/interpreting sties on the ground. PTTs are attached by collars, harnesses, subdermal anchoring, harpooning with a connected float, or by fur bonding (Taillade 1992).

PTTs are programmed to transmit every 50-90 seconds with a pulse width of about 0.33 seconds (Howey 1992, Samuel and Fuller 1996). (This narrow pulse is very important when working with animals such as dolphins because they have a mean surfacing time of only 0.75 seconds during which the signal must be sent [Taillade 1992]). When a satellite passes overhead, there is a 10-12-minute window during which a PTT's signal can be received. Two satellites are needed to obtain location information (Taillade 1992).

Since PTTs must be powerful enough to transmit a signal to satellites orbiting 800–4,000 km away (Howey 1992), their radiated power ranges from about 250 mW to 2 W (compared with 10 mW of radiated power in a typical conventional VHF animal-tracking transmitter) (Taillade 1992). A standard PTT collar, for example, requires three D-size lithium batteries which last 3-12 months, depending on specific duty-cycling (Fancy et al. 1988). For example, to prolong PTT life, some researchers program the transmitter to turn on for 1 day each 3. This duty cycle would yield three times the life of a PTT transmitting every day.

Early PTTs were designed to work with NIMBUS satellites (Kolz et al. 1980; Schweinsburg and Lee 1982; Timko and Kolz 1982). The next generation of PTTs were coordinated with the Argos Data Collection and Location System carried on Tiros-N weather satellites (Fancy et al. 1988; Rodgers et al. 1996). Currently, only the US/French Argos system is functional. The receiving systems are positioned on two NOAA (National Oceanic and Atmospheric Administration) polar-orbiting satellites resulting in complete global coverage (Taillade 1992). The location signal sent from the PTTs is relayed to receiving stations where researchers record and interpret the data (Priede 1992).

The rate of data collection by satellites varies according to topography and latitude. Keating et al. (1991) found location fix probability to be 11% of attempts in valley bottoms and 56% on mountain peaks. Also, since the satellites are in polar orbits, more overhead satellite passes occur, yielding more data at higher latitudes (Ancel et al. 1992).

Wildlife Research Using Satellite Telemetry

Satellite telemetry was first used to track animals in the early 1970’s (Buechner et al. 1971). Because early PTTs weighed several kilograms, satellite telemetry was only useful for large animals such as bears (Craighead et al. 1971) and elk (Craighead et al. 1972; Lentfer and DeMaster 1982). By the 1990's, improvements in PTT technology, reductions in weight of both batteries and housing, and use of solar cells have enabled satellite tracking of a wide variety of animals. The primary advantage of satellite telemetry is its ability to track animals over long distances and in remote areas.

Therefore, the best application of satellite telemetry is for far-ranging species such as migratory birds and marine mammals that are difficult or impossible to track with conventional VHF radio telemetry. Examples include dugongs (Marsh and Rathbun 1987), manatees (Mate et al. 1986, 1987; Rathbun et al. 1986), dolphins (Jennings and Gandy 1980; Woods and Kemmerer 1982), harp and hooded seals (Folkow and Blix 1992), humpback whales (Mate et al. 1983), sea turtles (Stoneburner 1982; Timko and Kolz 1982; Byles 1987; Hays 1992), basking sharks (Priede 1984), and polar bears (Kolz et al. 1980; Schweinsburg and Lee 1982; Fancy et al. 1988; Garner et al. 1989).

Satellite telemetry has also been useful in tracking the long-migrating albatross (Jouventin and Weimerskirch 1990; Weimerskirch et al. 1992) and otherwise elusive birds such as bald eagles, golden eagles, gyrfalcons, vultures, penguins, and various swans (Fuller et al. 1984;Strikwerda et al. 1985; Strikwerda et al. 1986; Priede et al. 1988; Higuchi et al. 1990; Ancel et al. 1992; Griesinger et al. 1992; Howey 1992).

Rosenberg and Petrula (1998) conducted studies involving surgically implanted satellite transmitters placed in surf and white-winged scoters from 1998 through 2000. The transmitters were designed to transmit weekly for about one year; however, the weekly signals were not always received.

Far-ranging terrestrial animals such as African wild dogs (Gorman et al. 1992), caribou (Pank et al. 1985; Craighead 1986; Curatolo 1986; Harrington et al. 1987; Fancy et al. 1988, 1989), muskoxen (Reynolds 1986), camels (Grigg 1987), wolves (Ballard et al. 1995; Merrill and Mech 2000), and elephants (Tomkiewicz and Beaty 1987) have also been tracked by satellite telemetry.

Advantages And Disadvantages Of Satellite Telemetry

As noted above, satellite telemetry’s greatest advantage is in tracking elusive and far-ranging species and minimizing the researcher’s travel/field time requirements. Theoretically, an animal can be tracked anywhere by a researcher in an office. Satellite telemetry involves a one-time handling of the animal until the PTT battery expires without repeated field trips by researchers. Furthermore, in some situations, such as far-offshore animals, satellite telemetry may be the only feasible means of tracking. Without satellite telemetry it would have been impossible to track emperor penguins traveling across sea-ice since there were no flights during winter over Antarctica, and tracking the penguins by foot on sea-ice was too dangerous (Ancel et al. 1992).

However, satellite telemetry is far less accurate than either conventional VHF radio-tracking or GPS radio-tracking (below). Satellite telemetry frequently reports locations whose accuracy varies from within 150 m to many kilometers (Keating et al. 1991). Locations are categorized into 4 classes (0-3) based on estimated location accuracy prior to receipt by the researcher (Taillade 1992).

Fancy et al. (1989) found 90% of satellite-based location estimates to be within 900 m of the known location, with a mean error of 480 m. The large degree of error is tolerable when tracking far-ranging species such as African wild dogs (Gorman et al. 1992), migratory birds and marine mammals, and long-distance dispersers but not for small-scale habitat analysis or animals using a relatively small area.

Another disadvantage of satellite-based tracking is that it is almost impossible to track the animal from the ground unless a VHF transmitter is built into the PTT. Many workers do incorporate such a transmitter, if only to facilitate recapturing the animal and retrieving the expired PTT for re-use.

Cost Of Satellite Telemetry Systems

Satellite telemetry can be viewed either as costly or economical. The cost of a single PTT unit is usually $3,000-$4,500, some 10-20 times as high as that for a conventional VHF transmitter (White and Garrott 1990). (If the PTT can be retrieved, refurbishment costs $150-$300). Additionally, the researcher must pay for the data acquisition and processing which can cost $90-260 per month per animal (Wilson et al. 1992).

However, satellite telemetry may be cost-effective in certain situations (Craighead and Craighead 1987; Harrington et al. 1987; Fancy et al. 1989). For example, on a cost/data-point basis, conventional VHF telemetry can be 43 times more expensive than satellite telemetry (5 yr study; 10 animals; 1 location per day) (Fancy et al. 1989).

Also, when working with remote species difficult to track, the cost of following the animal through nearly inaccessible terrain or distant oceans is eliminated by using satellite telemetry (Gorman et al. 1992). Furthermore, costs associated with field staff salaries and travel/living expenses, and for purchasing and receiving equipment are saved (Taillade 1992).

Satellite Telemetry Refinements

Technological improvements have extended the life of transmitting units (Taillade 1992). Most PTTs last from 3 months to 1 year depending upon duty-cycles. Similar to the duty-cycling feature of conventional VHF transmitting units, PTTs can be programmed to cycle on and off at regular intervals thereby conserving battery life. Argos markets a complete solar-powered, 28.5-g PTT for birds with a life of 1 year when duty-cycled to activate every 5 days for 8 hours. Also, photovoltaic cells in combination with NiCd batteries have extended transmitter life. For sea mammals, a sea-water trigger switch can activate a PTT when an animal surfaces. This saves battery life since the unit “sleeps” while the animal is submerged.

Besides reporting location data, new PTT’s can store a wide range of physiological, behavioral, and environmental data such as heart rate, dive depth, ambient temperature, etc. for later downloading to the satellite system (Tomkiewicz and Beaty 1987; Taillade 1992). Some PTT collars include a backup VHF beacon built in for locating the animal should the PTT fail, or for facilitating PTT retrieval for refurbishing. Gorman et al. (1992) used African wild dogs implanted with a VHF transmitter in order to facilitate later retrieval of the PTT satellite collar.

Differences among PTTs from various companies are also important to consider. Folkow and Blix (1992) compared the Toyocom T-2028 PTT and the Telonics SAT-103 PTT on harp and hooded seals. The transmission rate, power output, locations obtained, and location quality were all higher for the Telonics version. However, the Toyocom PTT withstood pressure at depths of 600 m while, the Telonics version was only reliable to depths of 400 m.

Global Location Sensing

A relatively unknown alternative to satellite telemetry is the global location sensor (GLS) system (Wilson et al. 1992), which, while not a telemetry system, yields similar information. The GLS system uses a device attached to an animal that calculates the animal's position by changes in the ambient light intensity related to the season and time of day, and two fixes per 24-hr period are possible for up to 220 days. The GLS is appropriate only when large location error (150 km) is acceptable such as when studying migratory movements of far ranging, remote species like polar bears or wandering albatross. Although this system is even less accurate than satellite telemetry, it is much less expensive. The GLS unit costs only about $200, and there are no fees for data acquisition or processing. Additionally, the GLS unit weighs only 113 g. However, no data can be accessed until the GLS unit is retrieved. Thus if the GLS unit retrieval is not successful, all data are lost.

Global Positioning System (GPS) Telemetry

Global Positioning System (GPS) tracking of animals is the latest major development in wildlife telemetry. It uses a GPS receiver in an animal collar to calculate and record the animal's location, time, and date at programmed intervals, based on signals received from a special set of satellites.

The GPS System

In 1973, the United States Department of Defense (DoD) began developing a Global Positioning System primarily to provide 24-hour, complete global satellite coverage for military purposes. In 1993 the GPS reached initial operational capacity when the 24th satellite was in place (Rodgers et al. 1996; Tomkiewicz 1996). Each satellite contains an almanac of all the other satellite positions, its current position, and the exact time.

With satellite telemetry, in contrast to GPS telemetry, the animal's PTT is a transmitter sending information to the satellite receivers which relay this information to a recording center on Earth. With GPS telemetry, a different set of satellites function as transmitters, while the animal's telemetry unit acts as a receiver. The signal information is used by the animal's telemetry unit to calculate its location based on current positions of satellites and the time taken for the signal sent from each satellite to reach the animal's receiving unit. These location data are then stored by the animal's unit for later unit retrieval or remote downloading.

At least four GPS satellites are always in view from any position on Earth, with each satellite orbiting approximately every 12 hours. This allows for 3D-position acquisition based on the four variables (latitude, longitude, altitude, and time/receiver clock bias). When line-of-sight to a particular satellite is obstructed due to, for example surrounding topography, a 2D position can be calculated using three satellites and three variables (latitude, longitude, and time/receiver clock bias). Altitude in a 2D fix is automatically calculated by either using the last known altitude from a 3D fix or by averaging a subset of the recent known altitudes (Rodgers et al. 1996).

Originally, the DoD incorporated intentional error into GPS signals received by civilian users for reasons of national security. This incorporation of intentional error with GPS data was called "Selective Availability" (SA). Under SA, accuracy was still very good, within 100 m 95% of the time (U.S. Department of Defense 1984).

However, using differential correction (DGPS), civilian users could correct for the intentional error (Moen et al. 1997) and also eliminate much of the error caused by ionospheric and tropospheric delays, with a resulting accuracy of 5 m, and with very expensive sophisticated correction equipment, within centimeters (Rodgers et al. 1996). In May 2000, the SA policy was abandoned by U.S. authorities, affording standard wildlife GPS units the approximate accuracy of differentially-corrected units under SA (Dussault et al. 2001).

Wildlife Research Using GPS Tracking

In 1994, Lotek Engineering, Inc. introduced the first animal-based GPS location system, the GPS_1000. Since its introduction, size has been reduced, longevity increased, and data storage and retrieval have improved. Today's standard collar consists of a GPS receiver and antenna, a VHF beacon system (for location backup and system verification), data handling and control hardware, and power supply (Rodgers et al. 1996).

Originally, the Lotek GPS_1000 collar weighed 1.8 kg and was too heavy for mid-sized mammals (Rodgers et al. 1996). A second generation of Lotek's original collar, the GPS_2000, is small enough for large cats, deer, wolves, and bears. Similarly, Telemetry Solutions offers GPS "Simplex" collars that weigh as little as 600 g, appropriate for an animal the size of a mountain lion or wolf. For these animals, the GPS Simplex collars are advantageous because they allow remote data downloading, whereas the Lotek GPS_2000 requires collar retrieval for data acquisition.

The GPS-Simplex is powered by two batteries, one for the GPS receiver, data storage, VHF beacon, report transmission, etc. and the other for the VHF beacon after the first battery has expired. When the collar is using the back-up battery, the pulse rate of the VHF beacon changes to alert the researcher that the first battery has expired and GPS fixes are no longer being taken. Once the collar switches to the back-up battery, the VHF beacon runs for approximately 6 more months during which time the researcher can try to retrieve the collar (see below). Telemetry Solutions also markets GPS backpack units as light as 70 g and minimalist GPS collars weighing 120 g.

General weight reduction has also indirectly affected longevity of GPS collars (Tomkiewicz 1996). For example, suppose a researcher previously used a 1,600-g collar on a large bear. If a 1,200 g collar became available for the same animal, 400 g would be available as "extra" weight for an increase in battery size and therefore, longevity. Longevity has also been increased by duty-cycling the VHF beacon to turn off when not needed (e.g. at night or for longer periods such as 3 months of hibernation).

The greatest drain on GPS collar batteries occurs when the system searches for satellite signals to acquire a location fix. The search time is critical to collar longevity. In many areas, location acquisition requires 2-4 minutes because of cover and topography. However, Televilt has produced a GPS collar (POSREC-Science) that can obtain a fix in 10 seconds under ideal circumstances. Further advances in decreasing the signal-acquisition time will greatly increase battery life.

Other recent advances in GPS telemetry include new features such as an indicator of time-in-mortality, a mechanism to automatically drop off the collar (for data acquisition and/or collar re-use), field-replaceable batteries, temperature and activity sensors, and remote two-way communication. These features help minimize researcher invasiveness to the animal by reducing animal handling time and by condensing the means for various studies into one data-collection device.

For example, using an automatic drop-off mechanism, the researcher does not need to recapture the animal to retrieve the collar. Remote two-way communication also minimizes animal contact since the communication link can be used in some models to reprogram scheduling of the fixes and other parameters of the unit without having to recapture the animal and retrieve the collar.

Field-replaceable batteries mean only one recapture instead of two. Units with batteries that are not field-replaceable must be returned to the company for refurbishing which requires a minimum of two more captures after the initial deployment, i.e. one to regain the collar with the expired GPS battery and another to place the newly refurbished collar back on the animal. Since field-replaceable batteries can be changed so much more quickly without having to ship them to a company, they also minimize lost opportunities for data acquisition while the GPS unit is not functioning.

Features such as time-in-mortality and temperature and activity sensors allow researchers to combine location-data-collecting projects with other physiological and ecological studies that may have previously required separate investigations. For example, researchers can use the GPS unit to temporally correlate the animal's activity (i.e. moving, resting, feeding) to ambient temperature while still obtaining location data.

Data Retrieval for GPS Tracking

Three main methods of data storage and retrieval are used in GPS telemetry: 1) on-board storage for later collar retrieval and subsequent downloading, 2) remote downloading to a portable receiver, 3) remote relaying through the Argos satellite system. There are advantages and disadvantages to each type of data storage and retrieval.

GPS Data Stored On Board. Collars with only store-on-board capabilities minimize researcher effort and invasiveness to the animal (only one handling required) since the collar is simply attached to the animal and later retrieved after an automatic or remotely triggered drop-off mechanism has released the collar from the animal. The data are then simply downloaded all at once from the collar (Merrill et al. 1998). Another advantage of the store-on-board collars is their relatively smaller size. Store-on-board collars contain comparatively smaller circuitry and are less complex than other types of GPS collars and thus can carry heavier (longer lasting) batteries for the same overall collar weight (Tomkiewicz 1996).

Since the store-on-board collars are less complex, they require less hardware (e.g. special field receivers) so are less expensive. Also, collars with remote or automatic break-away or drop-off mechanisms are advantageous because the retrieved collar can be sent back to the manufacturer for refurbishing and later reused resulting in increased cost savings (Merrill et al. 1998). ATS, Lotek, Telemetry Solutions, and Telonics all offer collars with store-on-board capabilities.

The main disadvantage when using a store-on-board-only GPS unit is data loss. If a GPS collar fails to release, all the data are lost unless the animal can be recaptured (Merrill et al. 1998). Also, since there are no intermediate data reports, the unit could malfunction and not collect data or may collect data at the wrong intervals. Some units contain VHF beacons that alert the researcher to the status of the last location-attempt. Nevertheless, the beacon only indicates that the unit appears to be functioning properly; it does not transmit any data and therefore, if the collar is not retrieved, all the data are lost (Merrill et al. 1998).

GPS Data Downloaded To A Portable Receiver. The second method of data retrieval ensures that at least partial data recovery will occur even if the collar malfunctions and fails to release from the animal. This method allows remote downloading directly to the researcher throughout the study. The collar is programmed to transmit data through a VHF signal (some systems use FM-relay devices or a UHF modem) to the researcher’s receiver.

Researchers can receive daily reports repeatable up to 5 times per day, or as infrequently as once per week. This timely retrieval of data allows biologists to supplement the location information with field data. For example, if location data from a carnivore indicates that the animal spent much time in a concentrated area, that may indicate the location of a kill. The researcher can then try to find the kill using a hand-held GPS navigation unit.

Interpretation of the GPS reports can also alert the researcher to a malfunctioning GPS unit or suggest changes in programming for more optimal data collection. With two-way communication, sampling regimens can be remotely altered if initial data reports indicate another location-acquisition routine may be more appropriate.

A vital feature with this type of GPS unit is long-term data retention following remote data transmission. Units that follow data transmission with a complete memory sweep are undesirable because often reception of the transmitted reports may not always be successful (Zimmerman et al. 2001). While intermittent reports are valuable in allowing data analysis throughout the study, long-term, on-board data storage completes the picture by allowing the researcher to fill in any blanks when the collar is retrieved. Telonics and Telemetry Solutions both offer collars with remote data downloading for large animals, but at present only Telemetry Solutions markets these collars for small-to-medium-sized mammals.

Some disadvantages to this method include the relative increase in complexity, and therefore, weight and expense of both the animal’s telemetry unit and the receiving equipment. Apart from the added cost of the equipment itself, it takes additional labor to retrieve the intermediate data reports. To retrieve the reports, the researcher must be within VHF receiving range, 5-10 km ground to ground, within 15-20 km air to ground, or for UHF, 15 km line-of-sight (Rodgers et al. 1996).

GPS Data Relayed by Satellite. The third main method of data retrieval and storage for GPS telemetry uses the Argos satellite system to relay the intermittent data reports. Thus the researcher needs neither to be in the field to collect the data reports, nor to maintain special receivers or other additional equipment. Lotek specializes in these types of GPS collars.

Disadvantages include the added bulk and weight of the animal's telemetry unit since transmitting data to satellites takes more power. This added weight limits the size of animal that can tolerate this type of GPS unit. In addition, the researcher must also pay Argos to relay data information through its satellites. Furthermore, to remotely change sampling schedules and report frequency, one must purchase a separate portable receiver/interrogator, adding expense.

Advantages And Disadvantages of GPS Tracking

Global Positioning System (GPS) tracking allows the researcher to obtain data on animal location in all weather as frequently as every minute or as infrequently as once per week with potential accuracy of within 5 m (Moen et al. 1996). While GPS units afford increased accuracy, their longevity is much less than that of conventional VHF units. VHF units for wolf-sized animals usually last about 4 years, whereas current GPS units rarely last longer than 1 year. GPS tracking is also expensive (see below).

However, per data point or for large, expensive studies, the costs of GPS tracking can be cheaper than for conventional VHF radio-tracking (see below). This is because for a given unit of researcher labor, GPS radio-tracking can gather many more location data. On the other hand, the types of data points differ. With GPS data, the points are usually serially correlated, whereas with standard radio-tracking they often are not, depending on their time intervals. In addition, biases in the data must be considered because of differential interference of various habitat types with the receivability of the GPS signal (Merrill 2002).

Furthermore, studies based on GPS tracking frequently use fewer individual animals because of the expense per GPS unit (Otis and White 1999). If the animals themselves are considered the study unit, this reduced sample size can cause data-analysis problems when generalizing about a population (White and Garrott 1990; Rodgers et al. 1996; Otis and White 1999).

Wildlife Research Using GPS Tracking

Since GPS telemetry for wildlife is relatively new, most studies have involved testing the reliability and accuracy of the equipment in varying environments and applications. Performance of various GPS collars have been tested for moose (Rempel et al. 1995; Moen et al. 1996; Rodgers et a. 1996; Dussault et al. 1999), white-tailed deer (Merrill et al. 1998; Bowman et al. 2000), and wolves (Merrill et al. 1998; Merrill and Mech 2000; Merrill 2002). The collars have functioned well, especially the most recent versions, which can be placed on an animal when it is most easily captured and can be programmed to begin duty cycling some months later (Nelson and Mech submitted).

No doubt, tests of GPS technology for wildlife will continue since new products are still rapidly forthcoming. For example, recent weight decreases have made remote-data-downloading GPS collars available for use on wolf-sized animals. Furthermore, with the establishment of baseline accuracies and statistically appropriate research applications, along with increased awareness of the potential for highly accurate data, increasing numbers of studies using GPS telemetry can be expected. Also, the cost should eventually decline to a more affordable level. Improvements such as these will hasten the use of GPS for a greater range of species.

Cost of GPS Telemetry Systems

A single GPS collar usually ranges from $3,000 to $4,500, about 10 times that of a VHF collar for mid-sized mammals (Merrill et al. 1998). An example start up package for one animal fitted with a remote-data-downloading GPS collar costs about $10,500. This includes a receiver (about $5,000), software with supporting cables (about $2,000), and a collar with a drop-off mechanism and one extra battery for field replacement (about $3,500). The cost of additional animals fitted with GPS collars is much less than the first in that the same receiver can be used for many collars. It is also important to note that GPS collars are reusable, with only drop-off mechanism ($275) and battery ($187) needing replacement.

Although GPS systems cost much more than VHF systems, this does not necessarily mean they are less economical. When cost/location is considered, as opposed to cost/animal, GPS collars can be the cheaper alternative and also save personnel costs since the study may be less labor intensive.

For instance, after examining multiple options including VHF and satellite telemetry, Rodgers et al. (1996) found that GPS-based telemetry was the most economical and logistically feasible method to track 60 moose located monthly with a subset of 20 moose located 35-50 times during three periods of intensive monitoring (early winter, late winter, and spring-summer-fall). On the other hand, for such studies as mortality investigations, the much longer life of VHF transmitters must be considered.

Determining Which Telemetry System To Use

Each telemetry system has its advantages and disadvantages. Within each system there are also options to specifically tailor the telemetry packages to the researcher's unique needs. However, some generalizations apply when deciding which type of telemetry is most appropriate for a particular study (Merrill and Mech 2000, Merrill 2002).

Studies for VHF Telemetry

If funding for a study is low or if a large number of animals are to be studied for long periods, VHF telemetry is the only option. Furthermore, VHF units can be used on virtually any animal whereas satellite and GPS telemetry units are often heavier and thus limited to medium-to-large mammals, except that solar-powered units can be used on birds. Another advantage of VHF units is their long history of use. Therefore, they are generally more reliable than the newer technology in GPS units.

However, VHF telemetry is generally more labor-intensive and less accurate. The costs of increased labor and transportation and the researcher's flexibility about data quality must be considered. While VHF is not as accurate as GPS telemetry, it can be combined with direct observations (following homing in on the animal) for finer-scale studies (Mech 1980).

Studies for Satellite Telemetry

Although satellite telemetry is more expensive than VHF tracking, in some cases it may be the only option, for example, for far ranging species such as transoceanic migratory birds or offshore marine mammals (Rempel et al. 1995). Satellite telemetry, as with conventional VHF telemetry, is not usually an appropriate method for fine-scale (25-250 m) habitat studies (Rempel et al. 1995).

Studies for GPS Telemetry

GPS telemetry is the most accurate form of tracking apart from visual confirmation of the animal's location, so GPS telemetry can be used with reasonable confidence for relatively fine-scale habitat studies (Moen et al. 1996; Rodgers et al. 1996). Additionally, GPS affords one benefit that visual confirmation may not. GPS units accurately locate an animal without the researcher's immediate presence. This means less researcher-introduced disturbance and therefore, potentially lower probability of unnatural animal behavior. This translates into less biased data.

A principal advantage of GPS units is the number of locations acquired per animal. For example in a 30-day period, 2,880 locations per animal can be acquired with a GPS unit programmed for 15-minute fixes. Additionally, GPS can be used in all types of weather all year round (Moen et al. 1996).

GPS telemetry is not without its drawbacks, though, cost being chief among them. When costs are prohibitive, researchers often compromise sound statistical sampling methods such that their results are based on a small number of animals carrying transmitters (Rodgers et al. 1996). Another disadvantage, when using GPS units is that they generally do not last longer than 1–1½ years.

Effects Of Radio-Tagging And Radio-Tracking

Regardless of which telemetry system is selected, potential effects on an animal's normal behavior must be considered whenever an animal is handled or instrumented (Cochran 1972; Marks and Marks 1987; Vaughan and Morgan 1992). It is to the researcher's advantage to minimize these effects since the goal of radio-tracking is to obtain data most closely reflecting the animals' natural behaviors.

Adverse effects from capturing and radio-tagging an animal can range from short to long-term and from apparently tolerable to severe or fatal (Birgham 1989). Whether specific effects are important in a study depends upon the objectives of the study (White and Garrott 1990). Many of the usual deviant behaviors last only 1-2 weeks. Therefore, some workers recommend that data should not be considered reliable until after at least 1 week of acclimation to the radio-tag (White and Garrott 1990).

Conceivably radio signals themselves could have some ill effect on the animal wearing a collar. However the ERP from VHF transmitters is so low that this possibility seems highly unlikely. Although the radiated power of PTTs is several orders higher than for conventional animal-tracking transmitters, there have been no findings of detrimental effects to the animal during 360 mS transmissions from the PTT (Taillade 1992).

An animal could display behavioral and energetic deviations as a result of the capture, handling, transmitter package, or presence of the radio-tracker. No data can actually prove that radio-tagging or radio-tracking an animal has no adverse effect. Rather, results can only show that no effect was detected when tested using the specified statistical power (White and Garrott 1990).

Generally, if a study animal maintains its weight, successfully mates, establishes and defends a territory, and/or produces offspring, and otherwise appears to look and behave normally, researchers consider the effects to be of minimal impact (Mech 1983, White and Garrott 1990). Researchers interested in informally monitoring adverse effects can watch for signs in their recaptured animals such as consistent weight loss from the first capture throughout the study (which would suggest movements are hindered and that the animal is likely more susceptible to predation), chaffing or hair loss under the collar, etc. (Mech 1983).

Effects on Birds

Experiments designed to detect adverse effects from radio-tagging and radio-tracking have focused mainly on birds. Most birds are relatively light and depend upon flying for survival. Therefore, one might expect that negative effects from the transmitter's weight and attachment packages would be easier to detect on a bird than on a large mammal, for example. Researchers studying the effects of radio-tagging on birds have been primarily concerned with the transmitter-to-body weight ratio (White and Garrott 1990).

While the "rule of thumb" for complete transmitter packages dictates that they weigh no more than 3-5% of the total body weight (Cochran 1980), subsequent studies have shown the importance of species-specific considerations (Caccamise and Hedin 1985; Aldridge and Brigham 1988; Anderka and Angehrn 1992). Some studies have examined not only the impact of the transmitter pack's weight and bulk, but also the effects of capture, handling, and tracking (Hill and Talent 1990; Taylor 1991).

Investigations such as the above have resulted in greater awareness of the adverse effects on the animal's behavioral patterns, survival, and reproductive success that a researcher might expect when conducting a radio-telemetry study. Direct effects of the transmitter packages themselves can include antennas and attachment packages becoming snagged in vegetation (Dunstan 1977; Jackson et al. 1977), animals themselves becoming entangled in loose collars or harnesses (Schladweiler and Tester 1972; Hirons and Owen 1982; Hines and Zwickel 1985), chaffing or feather loss (Bartholomew 1967; Hessler et al. 1970; Corner and Pearson 1972; Greenwood and Sargeant 1973; Perry 1981; Kenward 1982; Wywialowski and Knowlton 1983; Hines and Zwickel 1985; Jackson et al. 1985), electrocution in birds fitted with whip antennas while perched on wires (Dunstan 1977), and increased drag when swimming (Wilson and Wilson 1989), lifting, or flying (Pennycuick 1975; Pennycuick and Fuller 1987; Obrecht et al. 1988; Pennycuick 1989; Pennycuick et al. 1989).

Other avian investigations into the effects of radio-tagging have documented increased time spent in comfort activities such as preening (Greenwood and Sargeant 1973; Gilmer et al. 1974; Siegfried et al. 1977), attempts to remove the transmitter package (Perry 1981; Hooge 1991), weight loss (Perry 1981), abandonment of brood (Horton and Causey 1984), reduced time spent in flight (Gessaman et al. 1991), increased metabolism and energetic output (Gessaman et al. 1991), avoidance of water (Greenwood and Sargeant 1973), decreased courtship activity (Ramakka 1972), decreased feeding activity (Boag 1972), decreased clutch survival (Amlaner et al. 1978), lower survival rates in initially low-weight birds (Johnson and Berner 1980), greater susceptibility to predation (Sargeant et al. 1973; Siegfried et al. 1977; Erikstad 1979), and decreased reproductive success (Massey et al. 1988; Paton et al. 1991; Foster et al. 1992).

The above studies documenting adverse effects on avian reproduction are contrasted by those conducted by Boag et al. (1973), Johnson (1971), Amlaner et al. (1978), Kalas et al. (1989), Sodhi et al. (1991), and Taylor (1991) who found no significant effects on the reproductive success of red grouse, ring-necked pheasants, herring gulls, great snipe, merlins, or barn owls respectively. While the spotted owl study by Foster et al. (1992) found decreased reproductive success by birds fitted with a backpack harness, the studies also documented no difference in mean mass of spotted owls before and after wearing the radio transmitters. The researchers suggested the use of tail-mounted transmitters to avoid the apparent reproductive success problems caused by the larger backpack transmitters.

Kenward's (1977) study detected no difference in weight loss or dispersal behavior between goshawks fitted with transmitters and those fitted with leg bands. He also found comparable hourly feeding rates for sparrow hawks before being fitted with a transmitter and afterward (Kenward 1978).

Effects on Small Mammals

Although the majority of radio-tagged mammals are large predators or ungulates, most studies on the impacts of radio-tagging on mammals have concerned smaller mammals such as black-tailed jack rabbits, meadow voles, and lemmings (White and Garrott 1990). Instrumented small mammals have shown impaired movements (Banks et al. 1975), decreased digging ability (Corner and Pearson 1972), and decreased survival (Webster and Brooks 1980; Wywialowski and Knowlton 1983).

Aldridge and Brigham (1988) found that the 5%-body-weight "rule" caused adverse effects in maneuverability when applied to bats within a certain size range. That study showed that adverse impacts from the weight of transmitter packages should be examined not only uniquely for each species but also for size variations within each species if no such data from closely related species exist.

Effects on Large Mammals

Larger mammal radio-tagging impact studies have been limited but include river (Melquist and Hornocher 1979) and sea otters (Garshelis and Siniff 1983), mule (Goldberg and Haas 1978; Wenger and Springer 1981; Garrott et al. 1985) and white-tailed deer (Nelson and Mech 1981; Clute and Ozoga 1983), caribou (Pank et al. 1985), and mountain lions (Garcelon 1977).

Two studies involving the impacts of radio-tagging white-tailed deer noted adverse effects. Nelson and Mech (1981) conducted a mortality study with white-tailed deer fitted with collars taped with yellow (for ease in aerial spotting). They learned that the bright collars also allowed hunters to more easily see the deer and, therefore, the mortality data were biased with respect to hunting pressures. Clute and Ozoga (1983) noted that during cold spells white-tailed deer fawns with expandable collars collected heavy ice on their necks, probably from water splashed up when they crossed streams.

While both these studies found detrimental impacts, Hamilton (1976) saw no weight loss in leopards before and after fitting with transmitters. Gorman et al. (1992) recorded no adverse effects on African wild dogs when fitted with a PTT weighing just under 900 g. Neither did

Creel et al. (1997) find any adverse effects as measured by stress hormones in African wild dogs following typical anesthesia and radio-collaring.

Garrott et al. (1985) examined the hypothesis that mule deer fawns fitted with collars, as opposed to ear-tag transmitters, suffered greater predation rates due to collars providing coyotes a more secure grip on the fawn's neck. The authors found comparable survival rates between fawns with collars and those with ear-tag transmitters. Although their study included 91 animals, subsequent analysis (White and Garrott 1990) revealed that the sample size was short of the 96 animals required to detect a 30% difference in predation rates with 80% certainty. This example highlights the importance of study design with respect to statistical power when investigating impacts of radio-tagging and tracking.

Effects of Implanted Transmitters

Surgically implanting transmitters usually involves additional trauma to an animal and possibly requires recapture(s) to administer follow-up care (Morris 1980). However, several studies found no lasting negative impacts from the implant or the surgical procedure. Klugman and Fuller (1990) documented that implantation had no discernable effect on feeding, foraging, alert, and walking behaviors in sandhill cranes, and cranes dominant before surgery remained so afterwards. Van Vuren (1989) found similar pregnancy rates and mean litter sizes between female yellow-bellied marmots surgically implanted with transmitters and females not implanted. Reid et al. (1986) also concluded that implants did not affect the reproductive cycle in river otters; copulation, embryonic and fetal development, and lactation behaviors were all normal in surgically implanted river otters.

In slight contrast to the above, 3 of 10 beavers implanted developed adhesions between the transmitting capsule and peritoneal tissues (Guynn et al. 1987). One beaver died from intestinal obstruction as a result. The other 9 beavers were necropsied and had no indications of harmful pathology. The authors suggested encasing the implant in a layer of omentum during surgery to avoid complications caused by adhesion.

SOFTWARE USEFUL FOR MANAGING AND ANALYZING RADIO-TRACKING DATA

Regardless of type of radio-tracking used, the amount of data accumulates quickly. Thus many types of software are available to facilitate managing and analyzing them. Examples can be found in Appendix B.

TECHNOLOGICAL ADVANCES MINIMIZING IMPACTS TO ANIMALS

Advances in the construction of attachment packages and batteries have reduced adverse impacts of radio-tagging. For example, researchers creatively minimized radio-tag visibility in the cases of leopard (Hamilton 1976) and farm cat (Macdonald and Apps 1978) telemetry studies by painting the radio collars to match each feline's coat color and pattern.

Improved technology and decreases in battery weight now allow complete transmitter packages weighing as little as 0.8-1.2 g to last 20-30 days (Samuel and Fuller 1996). Since weight is a primary concern in radio-tagging, advances such as this are significant to minimizing adverse effects.

When researchers were confronted with the problem of whip antennas on red-cockaded woodpeckers snagging in tree bark, a more flexible antenna was used to alleviate this (Nesbitt et al. 1982). Also, Boshoff et al. (1984) and Karl and Clout (1987) incorporated weaker materials into collars used on birds to allow the collar to break away should it become snagged or entangled.

Expandable break-away collars are another advance. They have also been used on black bears (Strathearn et al. 1984), young bobcats (Jackson et al. 1985), young mountain lions (Garcelon 1977), caribou calves (Adams et al. 1995), and elk calves (Singer et al. 1997). Several attachment methods have been modified to free the animal from the transmitter. For example, collars incorporating elastic (Amlaner et al. 1978; Hirons and Owen 1982) or cotton threads (Karl and Clout 1987) deteriorate, loosen over time, and eventually fall off. However, the time required before the collar is dropped can be highly variable (Samuel and Fuller 1990) and consideration should be given to the interim period when the collar is still attached but poorly fitting and possibly impeding movements or chaffing excessively.

Researchers have also used harnesses that automatically release the radio package after a predetermined period and thereby avoid the slow "wearing away" interim period (Makcay 1974; Jackson et al. 1985). Similarly, GPS collars have remote drop-off mechanisms (Mech et al. 1990), so the collar can be retrieved without having to recapture the animal (Merrill et al. 1998).

Trap-transmitters have been employed on large-carnivore traps to help minimize injuries and capture-related stress (Hayes 1982; Nolan et al. 1984). The signal from the transmitter (which is attached to the trap and monitored throughout the trapping) changes pulse rate when the trap has been activated. The altered signal alerts researchers, which allows them to reach the trapped animal more quickly; thus the animal has less time to injure itself by frantic escape attempts. Transmitters can also be used to remotely trigger a trap.

Special "capture collars" minimize stress during recaptures as animals are remotely darted without the immediate presence of the researcher and without being restrained (Mech et al. 1984, 1990, DelGiudice et al. 1990, Mech and Gese 1992). Researchers locate the animal via telemetry and then signal its collar to fire a dart containing drugs into the animal. The collars are also equipped with a back-up dart. The researchers then follow the signal until the animal is under the effects of the injected drugs. This technique minimizes stress for the animal during recaptures (DelGiudice et al. 1990).

White and Garrott (1990) made five recommendations for researchers when implementing a radio telemetry study; 1) use the lightest-weight transmitter package possible, 2) select an inconspicuous package especially when dealing with animals that rely on cryptic coloration, 3) test the transmitter packages on captive animals first in a variety of environmental settings, 4) wait one week before collecting data to use in analysis, and 5) avoid handling/instrumenting an animal during any critical life history period (especially reproductive periods). Amlaner (1978) suggested that researchers should strive to use minimal-weight transmitter packages and non-restrictive harnesses.

If researchers follow the above suggestions, the benefits of radio-tracking studies should outweigh the potential adverse effects, resulting in a greater chance of obtaining unbiased data and of minimizing adverse effects for the instrumented animal.

MINIMIZING CONFLICT OVER WILDLIFE RADIO-TRACKING IN NATIONAL PARKS

As indicated earlier, any administrative functions in national parks intrudes on visitor experience. However, given the needs of the NPS to administer parks and gain information about national park ecosystems, a certain amount of intrusiveness is necessary. Because wildlife problems are so pervasive in national parks and because the public is so interested in the parks' wildlife, the NPS needs the best possible information about its wildlife. Radio-tracking, although intrusive, is not only the best way to obtain much of the needed information but it is often the only way.

Thus the NPS, faced with the dilemma of either forgoing the needed information or tolerating the intrusiveness of the information-gathering technique, can only try to minimize conflict over the intrusiveness of radio-tracking.

Minimizing such conflict can be done in several ways: (1) assessing the perception by park visitors of the intrusiveness of the technique so as to obtain an accurate picture of the problem; (2) educating park visitors (and staff) about the value and methods of radio-tracking, (3) urging researchers to consider the latest refinements in radio-tracking equipment, and (4) funding more expensive techniques if they are adequate and less intrusive.

Assessing the Problem

Documentation of the extent to which park visitors consider aspects of wildlife radio-tracking to be too intrusive is scarce to non-existent. Although the senior author has used radio-tracking in both Denali and Yellowstone National Parks, and was a member of a panel evaluating perceived intrusiveness of radio-tracking in Isle Royale National Park, he has never seen evidence that the public considers the technique intrusive. Instead, concerns that radio-tracking might be intrusive have come from park and concessions staff. While these concerns must be considered, they should not be accepted as representative of, or a substitute for, public opinion.

We highly recommend that the NPS conduct visitor surveys about the perceived intrusiveness of wildlife radio-tracking in its parks. Background information for the survey questions asked should explain what radio-tracking entails (including aircraft use, animal capture, and need for collars) and the type of information it provides, giving specific examples. Only through such research can the NPS know the true extent of the perceived problem.

Educating Visitors

Informing park visitors generally about radio-tracking and its benefits would help minimize misunderstandings and dissatisfaction with intrusive aspects of radio-tracking. Brochures, naturalist talks, and displays in kiosks and visitor centers could be used. Suggestions could even be made for visitors to try to see collars on animals so the visitors would regard those individuals as special. Specific information gained about radioed animals would enhance visitors' experience in the park, for example, maps with wolf or coyote pack territories, or of elk seasonal movements.

Use of Refinements

As indicated earlier, recent refinements in radio-tracking technology can reduce intrusiveness by minimizing numbers of times animals must be captured or that data must be obtained by in-field personnel. For example, for some studies, GPS collars hold promise to minimize in-field time by biologists. Urging researchers to consider such techniques will reduce potential conflict.

Funding of Refinements

When funding radio-tracking research, the NPS should consider providing sufficient funds to allow researchers to use more costly technology if doing so will reduce intrusiveness while still providing the information needed.

CONCLUSION

The constant need by NPS administrators for up-to-date information about park resources will usually conflict with the desire to keep the parks as pristine as possible. Because wildlife radio-tracking is so valuable for providing information and no substitute is in sight, the NPS can best deal with the dilemma by informing itself about the magnitude of the problem, proactively dealing with it through educating park personnel and visitors, and by minimizing the extent of intrusiveness through use of the best technology to do so.

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APPENDIX A
Radio Telemetry Equipment Suppliers

Mention of commercial manufacturers is made for convenience only. It does not constitute endorsement by the U. S. Government.

Advanced Telemetry Systems, Inc.
470 1st Ave. No., P.O. Box 398
Isanti, MN 55040 USA
Phone: 1-763-444-9267 / Fax: 1-763-444-9384
e-mail: sales@atstrack.com
http://www.atstrack.com
wide range of VHF telemetry equipment custom made for all species including marine applications, physiologic monitoring and automated data collection; also market programmable walkie-talkie size ICOM receivers

AF Electronics, Inc.
1906 Federal Dr.
Urbana, IL 61801 USA
Phone / Fax: 217-328-0800
receiving antennas

American Wildlife Enterprises
737 Silver Lake Road
Monticello, FL 32344 USA
Phone: 1-850-997-3551 / Fax: 1-850-997-3552
e-mail: BradAWE@aol.com
custom-built small avian and other miniature transmitters (usually <10g)

Andreas Wagener Telemetrieanlagen
Herwarthstr. 22
D - 50672 Koeln
Germany
Phone: +49(0) 221 514966 / Fax: +49(0) 221 9521867
e-mail: info@wagener-telemetrie.de
http://www.wagener-telemetrie.de
transmitters, receivers, antennaes, and other helpful equipment for the researcher with specialties in falconry and hunting supplies

Austec Electronics, Ltd. - NOT VERIFIED
#1006, 11025-82 Ave.
Edmonton, Alberta
Canada KT6G 0T1
Phone: 1-403-432-1878 / Fax: 1-415-449-3980
OR
17310 107th Ave.; Edmonton, Alberta, Canada T5S 1E9; Phone: 1-403-486-0511 / Fax: 1-403-489-3697

AVM Instrument Co., Ltd.
1213 South Auburn St.
Colfax, CA 95713 USA
Phone: 1-530-346-6300 / Fax: 1-530-346-6306
e-mail: sales@avinstrument.com
http://www.avinstrument.com
wide range of VHF equipment for mammals, birds and fish, traditionally used by herpetologists

Ayama-Segutel Radio Tracking
133 Bajos, Camí Ral
Mataró 08301
Barcelona, Spain
Phone: +34 (93) 7905862 / Fax: +34 (93) 7964932
e-mail: ayama@ayama.com
http://www.ayama.com
transmitters and receivers

Bally Ribbon Mills
23 N. 7th St.
Bally, PA 19503-1004 USA
Phone: 1-610-845-2211 / Fax: 1-610-845-8013
e-mail: BRM@ballyribbon.com
http://ballyribbon.com
teflon ribbon harness material

B & R Ingenierorgesellschaft mbH - NOT VERIFIED
Johann-Schill-Strasse 22
77806 March-Buchheim, Germany
Phone: 7665-3885 / Fax: 761-123794

Biomark
134 N. Cloverdale Rd.
Boise, ID 83713 USA
Phone: 1-208-378-4900 / Fax: 1-208-378-0487
email: marko@biomark.com
distributor of Destron and AVID tags, passive tags

Biosonics, Inc.
4027 Leary Way NW
Seattle, WA 98103 USA
Phone: 1-206-782-2211 / Fax: 1-206-782-2244
e-mail: bio@biosonicsinc.com
http://www.biosonics.com
acoustic detection & monitoring for aquatic environments

Biotelemetrics, Inc.
6520 Contempo Lane
Boca Raton, FL 33433 USA
Phone: 1-407-394-0315 / Fax: 1-407-394-0315
e-mail: biotran@ix.netcom.com
custom design of micro-miniature surgically implantable transmitters; infrared-powered transmitters

Bio Telemetry Tracking - NOT VERIFIED
18 Magill Rd.
Norwood, SA 5067
AUSTRALIA
Phone: +61-8-8362-6666 / Fax: +61-8-8362-7955
distribute receivers made by Yaesu, of Japan

Biotrack Ltd.
52 Furzebrook Rd.
Wareham, Dorset BH20 5AX
United Kingdom
Phone: +44(0) 1929 552 992 / Fax: +44(0) 1929 554 948
e-mail: info@biotrack.co.uk
http://www.biotrack.co.uk
telemetry systems and software

Bytel, Inc.
2525 South Shore Blvd.
Suite 202
League City, TX 77573 USA
Phone: 1-281-334-7171 / Fax: 1-281-521-1058
e-mail: bytel@bytel.com
http://www.bytel.com
remote radio monitoring systems

Communications Specialists, Inc.
426 W. Taft Ave.
Orange, CA 92865 USA
Phone: 1-800-854-0547 / Fax: 1-800-850-0547
e-mail: information@datasci.com
http://www.com-spec.com
R-1000 telemetry receiver; handheld walkie-talkie size; 352g; stores up to 999 frequencies; 3 yr. warranty

Custom Electronics of Urbana, Inc.
2009 Silver Ct. W.
Urbana, IL 61801 USA
Phone: 1-217-344-3460 / Fax: 1-217-344-3460
e-mail: customel@aol.com
http://members.aol.com/~customel/
receivers and antennas; custom made receivers and antennas, variety of bird transmitters with a specialty in raptors

Custom Telemetry and Consulting
1050 Industrial Drive
Watkinsville, GA 30677 USA
Phone: 1-706-769-4024 / Fax: 1-706-769-4026
specialize in custom made small animal telemetry packages to meet specific needs of both researcher and animal

Data Sciences International
4211 Lexington Avenue North
Suite 2244
St. Paul, MN 55126-6164 USA
Phone: 1-651-481-7400 (1-800-262-9687 US and Canada) / Fax: 1-651-481-7404
e-mail: information@datasci.com
http://www.datasci.com
physiological telemetry

Detlef Burchard, Dipl.-Ing. - NOT VERIFIED
Box 14426
Riverside Dr. No. 45
Nairobi, Kenya
Phone: 442371 / Fax: 442371

F&L Electronics
P.O. Box 19
Mahomet, IL 61853 USA
Phone: 1- 217-586-2132 / Fax: 1-217-586-5733
specialize in small transmitters for birds and fish, external and implantable, and a range of receivers and antennas

GFT - Gesellschaft fur Telemetriesysteme mbH - NOT VERIFIED
Eichenweg 26 (or is this 54?)
D-25358 Horst (or is this D-24582 Bordesholm)
Phone: +49-(0)4126-38793 (or 49-4322-699669) / Fax.: +49-(0)4126-38794 (or 49-4322-699671)
e-mail: rls.gftmbh@t-online.de
specializing in producing any kind of radio telemetry devices from small (<1g) transmitters up to Argos PTTs and GPS tags; develop hard- and software according to customer specifications

Global Tracking Systems (GTS), Inc.
17 Forest Dr.
Sylvan Lake, Alberta
Canada T4S-1H4
Phone: 1-403-563-5063 / Fax: 1-403-887-8866
e-mail: gtsdmt@telusplanet.net or gts-rjc@telusplanet.net
http://www.gtstrack.com
radio transmitter custom design and manufacture for fish and wildlife

H.A.B.I.T. Research, Ltd.
1-203 Harbour Rd.
Victoria, BC V9A 3S2
CANADA
Phone: 1-250-381-9425 / Fax: 1-250-381-9426
e-mail: info@habitresearch.com
http://www.habitresearch.com/
wide range of VHF, satellite, GPS transmitters; specialize in waterproof and floatable lightweight transmitters suitable for animals in size from robins to elephants

Hi-Tech Services
9 Devon Place
Camillus, NY USA 13031
Phone: 1-315-487-2484
email: JKenty@aol.com
wildlife and fish transmitters

Holohil Systems Ltd.
112 John Cavanagh Rd.
Carp, Ontario
Canada K0A 1L0
Phone: 1-613-839-0676 / Fax: 1-613-839-0675
email: info@holohil.com
http://www.holohil.com
radio transmitters; wide range of VHF equipment custom made for all species

Hydroacoustic Technology, Inc.
715 NE Northlake Way
Seattle, WA 98105 USA
Phone: 1-206-633-3383 / Fax: 1-206-633-5912
e-mail: support@htisonar.com
http://htisonar.com
manufacture a complete ultrasonic tag tracking system

ICOM America
2380-116th Ave. NE
Bellevue, WA 98004
Phone: 1-425-454-8155 / Fax: 1-425-454-1509
http://www.icomamerica.com
handheld programmable receivers

IMF Technology Gmbh
Groâe Müllroser Str. 46
15232 Frankfurt (Oder)
Germany
Phone: 49-0335-556040 / Fax: 49-0335-556049
custom design and manufacture of telemetry systems with a specialty on behavioral and physiological monitoring, also produce GPS collars and infrared sensing units

Johnson's Telemetry
Route 4, Box 313
El Dorado Springs, MO 65203
Phone: 1-417-876-5083 / Fax: 1-417-876-6844
e-mail: service@johnsontelemetry.com
http://www.johnsonstelemetry.com
specialize in hound recovery equipment; Tri-Tronics equipment

L.L. Electronics
P.O. Box 420
103 No. Prairieview Rd.
Mahomet, IL 61853 USA
Phone: 1-217-586-5327, 800-553-5328 fax: 217-586-5733
e-mail: lle@pdnt.com
conventional radiotelemetry

Lotek Wireless, Inc. (For Freshwater, Terrestrial, and Avian)
115 Pony Drive
Newmarket, Ontario
Canada L3Y 7B5
Phone: 1-905-836-6680 / Fax: 1-905-836-6455
e-mail: telemetry@lotek.com
http://www.lotek.com
GPS telemetry systems with remote downloading capabilities for large mammals, digital coding for transmitters, small transmitters for fish and fisheries management systems

Lotek Wireless, Inc. (For Marine)
114 Cabot Street
St. John's, Newfoundland
Canada A1C 1Z8
Phone: 1-709-726-3899 / Fax: 1-709-726-5324
e-mail: marine.telemetry@lotek.com
http://www.lotek.com
products include acoustic, radio, combined acoustic radio, archival and satellite systems for marine telemetry applications

Magenta Products, Ltd.
11a Radford Park Rd.
Plymstock, Plymouth
PL9 9DG United Kingdom
Phone: (0) 1752 862731 / Fax: 44 (0) 1752 862066
e-mail: sales@magenta-products.co.uk
http://www.magenta-products.co.uk
customized radio telemetry and data transmission
Mariner Radar Ltd - NOT VERIFIED
Bridleway, Campsheath, Lowestoft,
Suffolk NR32 5DN
England
Phone: 44-1502-567-195 / Fax: 44-1502- 567-762
transmitters used with satellites

Merlin Systems, Inc.
P.O. Box 190257
Boise, ID 83719 USA
Phone: 1-208-362-2254 / Fax: 1-208-362-2140
e-mail: info@merlin-system.com
http://www.merlin-system.com
telemetry equipment with falconry emphasis

Microlog Corporation - NOT VERIFIED
18713 Mooney Dr.
Gaithersburg, MD 20879 USA
Phone: 1-301-258-8400
local user terminal for satellite telemetry

Microwave Telemetry, Inc.
8835 Columbia 100 Pkwy.
Suites K & L
Columbia, MD 21045 USA
Phone: 1-410-715-5292 or 1-410-715-5293 / Fax: 1-410-715-5295
e-mail: microwt@aol.com
http://www.microwavetelemetry.com
specializing in miniature Argos satellite transmitters for tracking birds also elephants to whales) (smallest unit weighs under 30 grams complete), and digital coding transmitters and data collection systems

Mini-mitter Co., Inc.
P.O. Box 3385
Sunriver, OR 97707 USA
Phone: 1-503-593-8639 Fax: 1-503-593-8639
e-mail: rrushmmtr@aol.com
http://minimitter.com
specialize in small telemetry applications and physiologic and behavioral monitoring systems, automated data collection systems and software

Nature Conservation Bureau Ltd - NOT VERIFIED
36 Kingfisher Court
Hambridge Road
Newbury RG14 5SJ
United Kingdom
Phone: +44 1635 550380 / Fax: +44 1635 550230
email: 100347.1526@compuserve.com

North Star Science and Technology, LLC
Technology Center Bldg.
1450 S. Rolling Rd.
Rm 4.036
Baltimore, MD 21227 USA
Phone: 1-410-961-6692 / Fax: 1-603-462-5144 or 1-410-772-5985
e-mail: blakehenke@msn.com
http://www.northstarst.com
satellite-based telemetry; battery and solar powered PTTs through Argos system; software

Pacer - NOT VERIFIED
P.O. Box 1767
Dept. Biology – Agriculture College
Truro, Nova Scotia
Canada, B2N 5Z5
Phone: 1-902-893-6607 / Fax: 1-902-895-4547
LOCATE II, location estimate software

Polar Research Laboratory - NOT VERIFIED
6309 Carpinteria Ave.
Carpinteria, CA 93013 USA
Phone: 1-805-684-0441
local user terminal and uplink receivers for satellite telemetry

Promeon (Division of Medtronic)
6700 Shingle Creek Parkway
Brooklyn Center, MN 55430
Phone: 1-612-514-1000 / Fax: 1-612-514-1002
e-mail: adel.dimian@medtronic.com
http://www.mbbnet.umn.edu/company_folder/prm.html or www.medtronic.com
offering long life (7-10 year), hermetic power supplies chemistries include lithium iodine and lithium thionyl chloride

Sandpiper Technologies, Inc.
535 W. Yosemite Ave.
Manteca, CA 95337
Phone: 1-209-239-7460 / Fax: 1-209-239-1571
e-mail: Ann@Sandpipertech.com
http://wwwSandpipertech.com
video and surveillance systems for nests & burrows

Service Argos, Inc.
1801 McCormick Dr., Suite 10
Largo, MD 20744 USA
Phone: 1-301-925-4411 / Fax: 1-301-925-8995
e-mail: info@argosinc.com
http://www.argosinc.com
satellite system; provide required licensing and use privileges, and data transfer for Argos satellite system; do not provide any equipment or supplies

The Sexton Company
860 E St. NE
Salem, OR 97301-1223 USA
Phone: 1-503-371-6239 / Fax: 1-503-371-0994
e-mail: kens@thesextonco.com
http://www.users.quest.net/~kdsexton/
makes waterproof boxes for Telonics receivers and will also custom make housings for other receivers and electronic gear, and underwater housings for cameras, etc.

Sirtrack Limited
Private Bag 1403
Goddard Lane
Havelock North
New Zealand
Phone: 64-6-877-7736 / Fax: 64-6-877-5422
e-mail: sirtrack@landcare.cri.nz
http://sirtrack.landcare.cri.nz/
designs, builds, and packages radio tracking and telemetry equipment for wildlife research including satellite tracking systems and a wide range of VHF transmitters for all species

Smith-Root, Inc.
14014 Northeast Salmon Cr. Ave.
Vancouver, WA 98686 USA
Phone: 1-360-573-0202 / Fax: 1-360-286-1931
e-mail: info@smith-root.com
http://www.wildlifetracking.com
aquatic radio telemetry; specialize in fish transmitters using low frequencies but will custom make transmitters for other applications, fisheries research and management equipment; sell Pelican cases for transport

Sonotronics
3250 S. Dodge Blvd.
Suite 6
Tucson, AZ 85713 USA
Phone: 1-520-746-3322 / Fax: 1-520-294-2040
email: sales@sonotronics.com
http://www.sonotronics.com
acoustic radio transmitters; sonic tracking devices

Starlink, Inc.
500 Center Ridge Dr.
Suite 600
Austin, TX 78753 USA
Phone: 1-512-454-5511 or 1-800-460-2167 / Fax: 1-512-454-5570
e-mail: sales@starlinkdgps.com
http://www.starlinkdgps.com
develops and produces satellite, Loran, and automated VHF tracking systems for terrestrial and aquatic environments

Telemetry Solutions
1130 Burnett Avenue, Suite J
Concord, CA 94520 USA
Phone: 1-925-798-2373 / Fax: 1-925-798-2375
email: qkermeen@telemetrysolutions.com
http://www.telemetrysolutions.com
VHF and GPS telemetry; remote downloading GPS collar under 800g

Telemetry Systems, Inc.
P.O. Box 187
Mequon, WI 53092 USA
Phone: 262-241-8335 / Fax: 920-864-3411
OK22@greenbaynet.com
specializes in solar-powered transmitters for mammals and birds
Telonics, Inc.
932 East Impala Ave.
Mesa, AZ 85204-6699 USA
Phone: 1-480-892-4444 / Fax: 1-480-892-9139
e-mail: info@telonics.com
http://www.teloncis.com
wide range of fixed design VHF equipment as well as GPS and ARGOS tracking systems

Titley Electronics Pty Ltd
P.O. Box 19
Ballina, NSW 2478
Australia
Phone / Fax: country code - 61, number - 2-66-866-617
email: titley@nor.com.au
http://www.titley.com.au
transmitters, receivers, antennae, and other equipment including Anabat bat detectors

Toyocom
Coporate Headquarters
617 E. Golf Rd., Suite 112
Arlington Heights, IL 60005 USA
Phone: 1-847-593-8780 / Fax: 1-847-593-5678
http://toyocom.com
although Toyocom manufactures Argos transmitters for satellite systems for use in biotelemetry, they are normally not interested in small projects requiring custom manufacturing

TVP Positioning AB (Televilt International AB)
Box 53
SE-711 32 Lindesberg
Sweden
Phone: +46.581.17195 / Fax: +46.581.17196
e-mail: info@televilt.se
http://www.positioning.televilt.se
wide range of VHF equipment, automated tracking and data collection systems and data analysis packages, GPS systems

Vemco Limited
100 Osprey Dr.
Shad Bay, Nova Scotia
Canada B3T 2C1
Phone: 1-902-852-3047 / Fax: 1-902-852-4000
e-mail: sales@vemco.com
http://www.vemco.com
ultrasonic tags for aquatic animals including hydrophones and depth / temperature loggers

Wildlife Computers
16150 NE 85th St. #226
Redmond, WA 98052 USA
Phone: 1-425-881-3048 / Fax: 1-425-881-3405
e-mail: tags@wildlifecomputers.com
http://www.wildlifecomputers.com
time-data and satellite-linked recorders with software; specialize in dive data recorders and ARGOS tracking applications for marine vertebrates; time-depth recorder, satellite link, software

Wildlife Materials Inc.
1031 Autumn Ridge Road
Carbondale, IL 62901 USA
Phone: US 1-800-842-4537 and Canada 1-800-626-2704
e-mail: info@wildlifematerials.com
http://www.wildlifematerials.com
wide range of manufactured VHF equipment (transmitters, receivers, antennae, accessories) and automated data collection; implantable transmitters

Wildlife Tracking Systems - NOT VERIFIED
4 The Crescent
Wolverley
Kidderminster
Worcestershire
DY10 3RY
England.
Phone/Fax: 01562-850329 Mobile: 0860-832349
e-mail: wildlifetracking@easynet.co.uk
suppliers of quality falconry accessories

Wood-Ivey Systems Corp. (WISCO) - NOT VERIFIED
P.O. Box 4609
Winter Park, FL 32793 USA
animal PTTs and local user terminal for satellite telemetry

Ziboni Ornitecnica, s.r.l. - NOT VERIFIED
Costa Volpino (Bergamo)
Italy
Phone: 035-970434 / Fax: 035-972488

APPENDIX B
General Websites Offering Wildlife Software Packages and Links

http://wildlifer.com/wildlifesites/software.html

This site is beneficial for assessing what packages are available ranging from population analysis, home range analysis, statistical packages, etc. Corresponding links are provided.

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http://www.ecostats.com/

Ecological Software Solutions provides software products for Biology, Ecology, Wildlife & Fisheries, Forestry, Geography, and Other Environmental Sciences.

Home Range Analysis Software:

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http://nhsbig.inhs.uiuc.edu/www/home_range.html

This web page is an Ecology software server with related links for home range analysis.

Examples include:

Antelope- performs spatial statistics on data generated by mapping individuals in a population or from following a radio-tracked individual over time. It analyzes x,y data (not x,y,z) but accepts text files with additional columns which might be used to focus on subsets of the data.

Calhome - allows the user to pick from many home range analysis methods: minimum convex polygon, bivariate normal, harmonic mean, and adaptive kernel.

Dixon - uses a harmonic mean analysis as its method of finding the home range of an animal. It requires a math coprocessor.

HomeRange - primarily for use in the analysis of spatial data in animal behavior. This program has modules adapted from the Antelope program.

Home Ranger - calculates fixed or adaptive kernel home ranges of animals from radio-telemetry data. The program can also calculate standard error and bias in home range estimates by bootstrapping data and it can estimate effects of decretization (rounding) errors in telemetry data.

Kernelhr - performs kernel based estimates of two dimensional (bivariate) data. It is specifically designed for home range and population/species range analysis, but works well for any two dimensional data. Users may select between output of density and utilization distribution, change the size of the smoothing parameter and grid, and output values at the observation or on a grid.

Ulysses - a Mathematica implementation of home range estimation. Methods include adaptive kernel, tessellation, and minimum convex polygon (MCP).

Wildtrak - developed for the analysis of radio-tracking or other locational data for Macintosh computers. This program has many features including polygon and grid cell analyses for data description, a means to analyze both speed and distance of movement, and the analysis of interactions between animals. (For more Wildtrak info see also http://www.geocities.com/RainForest/3722/).

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http://www.esri.com/base/common/free.html

ESRI maintains a free software page, with downloads including the HRE (home range extension – see also http://blue.lakeheadu.ca/hre/) and reference links on GIS topics. The Animal Movement extension in ARCVIEW allows for spatial processing of location point data linked to various layers (such as topographic or attribute data layers).

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http://www.nsac.ns.ca/envsci/staff/vnams/locate.htm

Locate II - a DOS-based program to triangulate radiotelemetry bearings and calculate error ellipses. This replaces manually drawing bearings on maps and guesstimating where animals are located. It was published commercially by Pacer Computer Software, but as of June 2000 has been released into the public domain.

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http://www.neosoft.com/%7Einflo/demoa.htm#sharegen

This web site offers free downloads of wildlife software including packages such as:

Home Range Software: Antelope, Calhome, Dixon, Homer, Kernelhr, Mcpaal, Wildtrak, Ranges V

Population Parameter Analysis Software:

http://www.cs.umanitoba.ca/~popan/

This site is provides access to software for the analysis of fish and wildlife populations using marking and sighting methods such as POPAN-5, POPAN-6, SMOLT, and EAGLES.

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http://www.cnr.colostate.edu/~gwhite/software.html

This site offers population analysis software including:

BROWNIE computes survival estimates from banding (ringing) recovery data from young and adult animals.

Program MARK, a Windows 95, 98, or NT program, provides parameter estimates from marked animals when they are re-encountered at a later time. Re-encounters can be from dead recoveries (e.g., the animal is harvested), live recaptures (e.g. the animal is re-trapped or re-sighted), radio tracking, or from some combination of these sources of re-encounters.

CAPTURE computes tests to select a model from 11 possible models, and then the population estimate for capture-recapture data on closed populations.

DISTANCE provides an analysis of distance sampling data to estimate density and abundance of a population.

NOREMARK computes estimates of population size for a population with a known number of marked animals and 1 or more resighting occasions. Four different estimators are provided: joint hypergeometric maximum likelihood, immigration/emigration joint maximum likelihood, Minta-Mangel bootstrap procedure, and Bowden's estimator. Simulation procedures for determining estimator performance and necessary sample sizes are also provided.

RELEASE computes survival estimates and goodness-of-fit tests for a large class of survival experiments based on capture-recapture of marked populations. The general model is the Cormack-Jolly-Seber model for each experimental group (survival and capture probabilities different for each group), with a progression of submodels to the null model of the same survival and capture probabilities for all groups.

SURVIV is a FORTRAN code to compute survival estimates from general multinomial models. To run this program, you must have a FORTRAN compiler, because the model must be compiled into the SURVIV executable.

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http://www.neosoft.com/%7Einflo/demoa.htm#sharegen

This web site offers free downloads of wildlife software including packages such as:

Population software: Bandops, Bandzip, Biotools, Brownie, Capture, Comm, Contrast, Estimate, Jolly, Jollyage, Populus, Release, Surge, Uindex4S

http://www.ramas.com/

RAMAS software is for building ecological models linking landscape data (GIS) with population viability analysis. RAMAS programs incorporate species-specific data to predict the future changes in the population and assess the risk of population extinction or explosion and chances of recovery from a disturbance.

Radio-telemetry and Habitat Usage Software:

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http://www.neosoft.com/%7Einflo/demoa.htm#sharegen

This web site offers free downloads of wildlife software including packages including:

Radio-telemetry software: Triang.zip

Habitat usage software: MacComp, Biopak

For more information on specific radio-telemetry software programs see:

White, G. C., and R. A. Garrott. 1990. Analysis of wildlife radio-tracking data. Academic Press, San Diego, CA. 383 pp.

APPENDIX C
Scientific Names

Birds:

Bald eagle (*Haliaeetus leucocephalus*)
Barn owls (*Tyto alba*)
Emperor penguin (*Aptenodytes forsteri*)
Golden eagle (*Aguila chrysaetos*)
Great snipe (*Gallinado media*)
Griffon vulture (*Gyps coprotheres*)
Gyrfalcon (*Falco rusticolus*)
Herring gull (*Larus argentatus*)
Merlin (*Falco columbarius*)
Northern goshawk (*Accipiter gentilis*)
Red-cockaded woodpecker (*Picoides borealis*)
Red grouse (*Lagopus lagopus scoticus*)
Ring-necked pheasants (*Phasianus colchicus*)
Sandhill crane (*Grus canadensis*)
Spotted owl (*Strix occidentalis*)
Surf scoter (*Melanitta fusca*)
Swan (*Cygnus spp*.)
Wandering albatross (*Diomedea exularis*)
White-winged scoter (*Melanitta perspicillata*)

Mammals:

African wild dog (*Lycaon pictus*)
Bats (*Chiroptera*)
Bison (*Bison bison*)
Black bear (*Ursus americanus*)
Black rhinoceros (*Diceros bicornis*)
Black-tailed jack rabbit (*Lepus californicus*)
Bobcat (*Felis rufus*)
Bottlenose dolphin (*Tursiops truncatus*)
Brown lemming (*Lemmus trimucronatus*)
Camel (*Camelus spp.*)
Caribou (*Rangifer tarandus*)
Coyote (*Canis latrans*)
Dugong (*Dugong dugon*)
Elk (*Cervus elaphus*)
Elephants (*Elephantidae*)
Eurasian badger (*Meles meles*)
Farm cat (*Felis catus*)
Gray wolf (*Canis lupus*)

Grizzly bear (*Ursus arctos*)
Harbor seal (*Phoca vitulina*)
Harp seal (*Phoca groenlandica*)
Hooded seal (*Cystophora cristata*)
Humpback whale (*Megaptera novaeangliae*)
Leopard (*Panthera pardus*)
Lion (*Panthera leo*)
Manatee (*Trichechus manatus*)
Meadow vole (*Microtus pennsylvanicus*)
Moose (*Alces alces*)
Mountain lion (*Felis concolor*)
Mule deer (*Odocoileus hemionus*)
Muskox (*Ovibos moschatus*)
North American beaver (*Castor canadensis*)
North American river otter (*Lutra canadensis*)
Polar bear (*Ursus martitimus*)
Pronghorn (*Antilocapra americana*)
Sea otter (*Enhydra lutris*)
Tiger (*Panthera tigris*)
Western European hedgehog (*Erinaceus europaeus*)
White-tailed deer (*Odocoileus virginianus*)
Wild boar (*Sus scrofa*)
Wolf (*Canis lupus*)
Yellow-bellied marmots (*Marmota flaviventris*)

Fish, Amphibians, and Reptiles:

Basking shark (*Cetorhinus maximus*)
California toad (*Bufo boreas halophilus*)
Eastern hellbender (*Cryptobranchus alleganiensis*)
Northern water snake (*Nerodia sipedon*)
Sea turtle (*Caretta caretta*)

APPENDIX D
Comparative Characteristics of VHF, Satellite, and GPS Collar telemetry[1].

Characteristics	VHF	Satellite	GPS Collar
Collar Weight[2]	560 g	520 g	830-920 g
Initial investment per collar	$300	$3,000	$3,000
Cost per 100 locations	high	medium	low
Data retrieval potential	high	high	low to high depending on likelihood of dispersal
Accuracy	medium to high depending on effort	($\pm$ 500 m)	high; usually accurate to 20 m
Longevity	$\leq$ 6 year	1-12 month depending on interval between location attempts	3 week-10 month depending on interval between location attempts
Interference from weather	high (aerial telemetry)	none	none
Interference from habitat	low	high	high
Interference from topography	medium	high	high
Intrusiveness after collaring	high	none	none to high[3]

[1] Adapted from Merrill (2002); [2] Collar weight varies by species and collar manufacturer; weights given are for wolves; [3] Depends on frequency of data downloading.