

B. Satellite Tracking

Meyburg, B.-U. and M. Fuller. 2007. Spatial tracking; B. Satellite tracking. pp. 242-248 in D.M. Bird and K.L. Bildstein. eds. Raptor Research and Management Techniques. 2nd ed. Hancock House Publishers. Ltd. Surrey, B.C., Canada and Blaine, Washington.

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INTRODUCTION

Satellite telemetry has revolutionized the study of raptor migration and life histories and will continue to do so in the future (Table 1). This is because tracking systems used in satellite telemetry can regularly estimate and record an individual's location worldwide for several years. Satellite telemetry with birds started in the 1980s (Strikwerda et al. 1986). Since then, satellite telemetry has been based on Ultra High Frequency (UHF) technologies such as the Argos system, that includes the Collecte Localisation Satellites (CLS). More recently, transmitters and Global Positioning Systems (GPS) receivers have become small enough to use on birds. In some cases GPS satellite telemetry will soon supersede land-based VHF tracking.

The Argos System

Satellite telemetry for raptor studies has used the Argos

system. Individual birds must be able to carry transmitters, called Platform Transmitter Terminals (PTTs), weighing about 5 g or more. The Argos system provides location estimates and sensor data (e.g., battery voltage, activity, temperature, pressure) from PTTs anywhere around the world. The basics of operation are described in the Argos User Manual (www.argosinc.com/system_overview.htm). Additional recent information is available in the *Proceedings of the Argos Animal Tracking Symposium, 24–26 March 2003* (CLS America 2003), which is available on CD from CLS America, 1441 McCormick Drive, Suite 1050, Largo MD 20774.

Location Estimates of Transmitters by Argos

PTTs are located using the Doppler phenomenon. Polar-orbiting satellites carry Argos receivers. As a satellite approaches the PTT, the frequency received will be higher than the nominal transmitted frequency (401.650 MHz), whereas frequencies lower than 401.650 MHz will be received at the satellite as it moves away from the PTT. At the point of inflection of the Doppler curve, that is, when the received and transmitted frequencies are equal, the position of the transmitter will be perpendicular to the satellite ground track. The system estimates two possible PTT locations, which are symmetrical on each side of the satellite ground track. Argos selects one of these as plausible, but biologists should confirm the validity of the location selected by Argos.

Location estimates based on PTT transmissions and the Argos satellite system are assigned to location classes (LC). "Location accuracy varies with the geometri-

Table 1. Topics and questions regarding raptors for which data from satellite telemetry have or are expected to provide information. Some references are provided, and more can be found at the U.S. Geological Survey Raptor Information System (<http://ris.wr.usgs.gov/>). The keywords below and others can be used to find citations to publications listed in the Raptor Information System.

Annual Movements	<ul style="list-style-type: none"> • Annual movements (Brodeur et al. 1996, Fuller et al. 2003, Meyburg et al. 2004b, Laing et al. 2005, Steenhof et al. 2005) • Differences among years (Alerstam et al. 2006)
Migration	<ul style="list-style-type: none"> • Mapping routes of migrating raptors (Meyburg et al. 1995a, 1995b; Brodeur et al. 1996, Fuller et al. 1998, Ellis et al. 2001) • Individual variation (Alerstam et al. 2006) • Ecological barriers, leading lines (sea, mountains, deserts) (Meyburg et al. 2002, 2003) • Bottlenecks; do all individuals pass a narrow area, at what time? (Fuller et al. 1998) • Navigation and orientation (Hake et al. 2001, Thorup et al. 2003a, 2003b, 2006b) • Migration period and timing (Schmutz et al. 1996, Kjellen et al. 2001, Meyburg et al. 2004b) • Age and sex differences, breeding status (Ueta et al. 2000, Ueta and Higuchi 2002, Hake et al. 2003, McGrady et al. 2003, Meyburg et al. 2005, 2006, Soutullo et al. 2006b) • Speed and altitude of migration (Hedenström 1997, Kjellen et al. 2001) • Variation throughout migration (Meyburg et al. 2006) • Daily distances, travel rates (Fuller et al. 1998, Meyburg et al. 1998, Soutullo et al. 2006a) • Daily behavior, stopovers (time of starting and stopping), hunting (Meyburg et al. 1998) • Weather conditions (Meyburg et al. 1998, Thorup et al. 2003b, 2006a) • Ecological conditions along migration routes
Winter or Austral Summer	<ul style="list-style-type: none"> • Geographical situations of wintering grounds (Woodbridge et al. 1995, Martell et al. 2001, Haines et al. 2003, Higuchi et al. 2005, Steenhof et al. 2005) • Discovery of unknown wintering grounds (Meyburg et al. 1998) • Ranges on wintering grounds (McGrady et al. 2002) • Fidelity to the same area in successive years (Fuller et al. 2003)
Nesting Season	<ul style="list-style-type: none"> • Home range size, habitat use, and territorial behavior (Meyburg et al. 2006) • Dispersal, philopatry (Rafanomezantsoa et al. 2002, Steenhof et al. 2005) • What accounts for later or earlier arrival in spring at the nest site (influence of weather during migration, later or earlier departure to wintering grounds) (Meyburg et al. 2007b) • Pair continuity over a number of years (Meyburg 2007a) • Behavior of nonbreeding adults, floaters (arrival, fidelity to nest site after failed nesting attempt, possible nomadism) (Meyburg 2007b)
Movements during Immature Stage	<ul style="list-style-type: none"> • Return to breeding area or remain on the “wintering grounds” (Meyburg et al. 2004a) • Ranging behavior (Meyburg et al. 2004a)
Survival, Mortality, Threats	<ul style="list-style-type: none"> • Human activity (Eastham et al. 2000) • Other causes (Goldstein et al. 1999, Hooper et al. 1999, Henny et al. 2000, Millsap et al. 2004, Steenhof et al. 2006) • Fate of release birds (Rose et al. 1993, Launay and Muller 2003, Dooley et al. 2004)

cal conditions of the satellite passes, the stability of the transmitter oscillator, the number of messages collected and their distribution in the pass. This means in particular that a given transmitter can have locations distributed over several classes during its lifetime. Classes for which accuracy is estimated and their related values: Class 3: better than 150 m on both axes, 250 m radius, Class 2: better than 350 m, 500 m radius, Class 1: better than 1000 m, 1500 m radius, Class 0: over 1000 m, 1500 m radius. These are estimations at one sigma.” (www.cls.fr/html/argos/general/faq_en.html).

Argos location methods are based on three major assumptions: (1) transmission frequency is stable during the satellite pass, (2) the PTT is motionless during the satellite pass, and (3) the altitude of the PTT is known. The LC assigned by Argos usually underestimates the error associated with wildlife applications largely because these assumptions often are violated to some extent when the PTT is on an animal (e.g., Britten et al. 1999, Craighead and Smith 2003). Usually, the accuracy given by Argos is better for the latitude than for the longitude. The given accuracy (e.g., 1 km for LC 1) does not mean that all of the calculated locations (and attributed to LC 1) fall within 1 km, but that about one sigma (one standard deviation) of all estimates are in the nominal accuracy range.

It is important to remember that the best two LCs (LC 2 and LC 3) usually are achieved only 10% to 15% of the time from birds. This occurs for numerous reasons, not the least of which is that many wildlife PTTs do not transmit 1 W of power, upon which the Argos system was designed. Power often is programmed to 0.15 to 0.25 W to conserve energy for prolonged PTT operation. Power output in solar-powered PTTs is adjustable (e.g., from 0.1 to 0.5 W). Reduced radiated power can result in fewer location estimates, and consequently fewer data with which Argos can estimate locations most accurately.

Argos routinely provides Standard LCs (LC 3, LC 2, LC 1, see above), but also can provide Auxiliary LCs (LC 0 > 1000 m, LC A and LC B = no estimate of location accuracy, and LC Z = invalid locations). The Auxiliary LCs are especially important because often there are few Standard LCs from wildlife tracking. Furthermore, the best LC classes do not always include the most accurate location estimates. Thus, wildlife researchers, especially those tracking birds, will want as many location estimates as possible from which to select appropriate data.

Location-estimate error from a given project can

vary dramatically depending on the speed of the animal and its behavior, including changes in elevation or altitude (www.cls.fr/manual/; see Appendix 2, Argos location), environmental variables (topography, vegetative cover, marine, atmospheric conditions), and data acquisition and analysis options. Users may specify to Argos values for some factors (e.g., PTT velocity, altitude) and discuss options (e.g., use of digital elevation model, multi-satellite service), and Argos will incorporate these in the estimation procedures. Users also should consult with equipment manufacturers to maximize performance (e.g., PTT power, transmission repetition rate) for the circumstances and objectives of the study. Biologists must determine if the Argos system is appropriate for their objectives, especially if they require regular location accuracy of less than 1 km.

Reduced Argos Performance

A significant difference in actual receptions of PTT transmissions exists in the European region and in Asia (Mongolia, China, Japan), and thus can reduce receptions to less than 10% of the expected data. The affected area is about the size of the satellite footprint (5,000 km in diameter) and seems to be centered in the region of southern Italy (Howey 2005). The cause is ambient broadband noise of significant amplitude around the Argos operating frequencies, which causes interference and affects all PTTs, including GPS models. It essentially limits the number of signals that are received by the satellite (Gros and Malardé 2006). We recommend that users contact CLS to discuss their specific requirements and take advantage of ways to optimize Argos system performance.

Argos Data-validation Procedures

Researchers should examine and carefully filter location estimates before selecting those for analyses. Filtering or data validation procedures usually involve establishing criteria based on animal movement capabilities and behavior (e.g., maximum speed, local versus migration movement; Hays et al. 2001) and inspecting the Argos data for time and distance relationships among location estimates. Many LC 0, LC A, and LC B class points might need to be discarded by filtering, but so might some LC 1, LC 2, and even LC 3 class points. Careful screening also might reveal that some LC 0, LC A, and LC B locations are well within the distance that an animal could have traveled during the period

between location estimates, and within a direction that is logical.

Raptor researchers must remember that locations from Argos are estimates and that accuracy and precision vary with animal and environmental factors that are largely unknown. In our experience, the proportion of higher quality LCs (LC 2 and LC 3) varies among PTT-marked animals. Therefore, we recommend that each person establish criteria for the study objectives, species, and environment and then apply those criteria when selecting the location estimates to be used in analyses.

Data Transmission through the Argos System

PTTs transmit a coded identification and data from up to 32 sensors. The signals are digitally encoded on a pulse width of ~ 0.36 seconds and a pulse interval usually between 40 and 90 seconds. The transmitting schedule (i.e., the duty cycle) can be programmed for more transmissions during different periods (e.g., seasons), which can prolong the operational life of battery-powered PTTs.

Transmissions from PTTs are received on polar orbiting satellites and are relayed to processing centers in France and the United States. Records of processed data can be distributed to users in a variety of formats, including Internet access to data received about four hours previously. The cost of data acquisition from Argos varies according to the different agreements between countries and Argos. Costs are assessed as a fee for use of each active platform, for hours of use per day, automatic data distribution service (data via email), fax, telnet, data acquired from the Argos website, and monthly compact discs (CD).

GPS Location of Transmitters

The GPS provides location accuracy to within a few meters. A GPS receiver can be integrated with an Argos PTT. A GPS receiver collects transmissions from at least four satellites, enabling computing of position (in three dimensions), velocity, and time. GPS units can be programmed to collect data at pre-set intervals. Data can be logged in memory and downloaded from the unit (usually requiring recapture), or they can be coded in PTT messages and relayed to users via the Argos system. The GPS estimates are transmitted to Argos during the "on time" of a PTT duty cycle.

The GPS receiver requires considerable energy. Thus, there are radio-tag size and longevity constraints that come into play when using battery power for bird studies. Alternatively, solar-powered GPS-PTTs weigh as little as 22 g. These units include sensors and a 12-channel GPS receiver.

Selection of the PTT

A crucial consideration when choosing a unit is how the PTT size, weight, and attachment might affect the bird (Murray and Fuller 2000). The energy requirements for satellite telemetry limit the minimum mass of units to about 5 g. The mass of the transmitter increases the energy the bird must expend for locomotion. Battery mass and surface areas of solar arrays also are limiting factors for unit size.

Deciding whether to use battery- or solar-powered tags must be made early in study planning. Battery-powered PTTs offer generally reliable performance, but have the disadvantage of a rather short operating life, thus long-term studies (more than three years) normally are not possible. Using 30- to 90-g battery-powered PTTs we regularly received locations from 6 to 18 months, depending on radiated power and duty cycle. Solar-powered transmitters can provide locations for up to several years, and the regularity of data is dependent on enough light on the solar array to charge a battery or capacitor with energy for transmission of the radio signal. Solar-powered GPS-PTT tags need more energy than PTTs. Thus, the problem of recharging these tags is even more acute. One must be sure the feathers do not occlude the solar array to the extent that there is insufficient exposure to light for minimal PTT function. Bird habitat use, such as under-canopy or cave nesting, also can affect solar charging.

The decision of whether to use solar or battery-powered PTTs depends not only on the geography and expected movements of the species to be studied, but also on other factors such as budget, lifestyle of the species, aim of the study (long- versus short-term), etc. In 2007 the price of a PTT was about \$3000 (U.S.), and that of a GPS-PTT was about \$4000. Costs of delivering data (see above) for several years can be as much or even more than the tag price, depending on how tags are programmed and what Argos services are used.

Attachment of Transmitters

Radio tags can be mounted on tail-feathers, legs, and

wings, but in most studies they are attached to the bird's back using a harness (Fuller et al. 2005). These "backpacks" have the advantage of being fixed near the center of lift which is best for high tag mass. Tags can be fitted to nestlings just before fledging and can be tracked for several years. Most researchers use Teflon[®] ribbon as harness material, but we found that some raptors (e.g. Asian Imperial Eagles [*Aquila heliaca*] and Lesser Spotted Eagles [*A. pomarina*], Prairie Falcons [*Falco mexicanus*]) remove tags by pulling and cutting through the Teflon[®] strips with their beaks (Steenhof et al. 2006). The potential complication of feathers over the solar panels on backpacks might be overcome by incorporating a feather guard (Snyder et al. 1989) or thick neoprene rubber on the bottom of the transmitter to elevate the solar array. These modifications might create additional aerodynamic drag and thus, energy needed for flight.

What Causes Termination of Transmissions?

Manufacturers can program a unit to stop transmitting, but most researchers probably would like to receive transmissions for as long as possible. Battery-powered units transmit information about battery voltage so that one can predict depletion of the battery energy. Often however, failure to receive transmissions occurs earlier than expected, raising a question as to what has happened. The causes of failure to receive data are sometimes difficult to determine.

Juvenile and immature birds often die from "natural causes," or perish from persecution. Adults also are subject to heavy persecution in many parts of the world or are killed by electrocution, collisions, etc. Nevertheless, based on observing the bird, recapturing it, or finding it dead much later, we confirmed that several solar-powered PTTs had failed while the birds were alive. In some cases we, or the manufacturer, were unable to determine a reason for the failure. Study planning should account for death of radio-marked birds and the failure of some transmitters.

Our record for long-term tracking is an adult female Greater Spotted Eagle (*A. clanga*). The bird was fitted with a PTT in July 1999 that was still transmitting data in August of 2007. An adult male Lesser Spotted Eagle was tracked as far as Israel on its way back to the breeding grounds almost 6 years after having been marked. When it arrived one month later in Germany we observed the bird with its PTT without an antenna. An

Osprey also lost or removed the antenna after only a few months. It is much easier to find the reasons for tag failure in breeding adults that return to their nest site year after year. There are methods for locating PTTs that are transmitting from a dead bird or detached from the bird (Howey 2002, Bates et al. 2003, Peske and McGrady 2005). Finding the PTT can provide valuable biological information and be cost-effective because most units can be refurbished for about \$300 to \$500, and used again.

Tracking Options

Finally, satellite telemetry is one of many options for marking raptors. Before deciding to use telemetry we encourage persons to consider carefully (1) their objectives and (2) the possible effects of marking on the birds and their implications for the results. The literature provides many examples of studies in which satellite telemetry has provided valuable information (Table 1). Consultation with manufacturers about options can be very useful, and is especially important for programming the function of transmitters and receivers to maximize performance.

ACKNOWLEDGMENTS

We thank A. Aebischer, P. Howey, B.D. Chancellor, and K. Bates for their helpful comments on drafts of our manuscript.

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