

Possibilities for global tracking of small (30-200 gram) birds

Satellite tracking of animals with the ARGOS satellites at an accuracy of ten to hundreds of meters has become common in recent years (Weimerskirch et al. 1993; Bevan et al. 1995). Over the past decade improvements in technology and design have resulted in transmitter weight reductions from more than 100 grams to about 20 grams. The basic limitation of the ARGOS system is that it requires animal transmitters that radiate about 100 milliwatts (+20 dBm). A new series of satellites may allow use of 50 milliwatt (+17 dBm) transmitters weighing perhaps 14 grams (Howey 2003)

These could be used on birds weighing ~500 grams if 3% of body weight is tolerable according to U.S. Fish and Wildlife Service regulations. Further transmitter weight reduction is unlikely because of battery weight and system power requirements (personal comm. 2003 Paul Howey, Microwave Telemetry).

Alternatively, bird transmitters for conventional terrestrial tracking of songbirds weigh about 0.4-1 gram, have radiated power of about 0.1 milliwatt (-10 dBm), and a working life of about 1 month. Life can be extended to several months by slowing the pulse rate or much longer by increasing weight to 2 grams. ARGOS transmitters requires several hundred times as much power.

The feasibility of tracking from the ISS: a simple example.

Feasibility of detection of -10 dBm transmitters from satellite altitudes can be demonstrated by calculations based on >40 years of radio-tracking experience. At 220 MHz, path loss over a distance of 400 Km (height of the ISS) is 132 dB (Figure 7c)(Crombie 1989); i.e., a transmitter radiating -10 dBm (isotropically) will excite an isotropic receiving antenna 400 km away with a signal of -142 dBm. A receiver antenna with 6dBi linear polarization gain (a 9 dBi-gain helix) will improve the received signal to -

136 dBm (Kraus 1988). A -136 dBm pulsed signal (18 ms pulse width and several seconds or shorter pulse interval) is easily audible in current wildlife tracking receivers. These numbers are valid for transmitters directly under the satellite.

A 9 dBi-gain helix antenna will have a half-power (-3 dB) beam width of about 25 degrees and therefore a gain of 3 dBi around the circumference of a circle 185 km in diameter ($\tan 25 \times 400 \text{ km}$) centered under the satellite. Adjusting for both the 3 dB off-axis loss due to the antenna pattern and the increased distance ($400 / \cos 25 = 442 \text{ km}$), the received signal level will be -139.8 dBi for -10 dBm transmitters on this circumference; this is still an easily detected level for wildlife receivers. These receivers typically have a noise figure of 3 dB and bandwidth common to SSB reception (ca. 2.5 KHz). The detection is marginal at -143 dBm, but still possible even at -145 dBm (albeit with errors).

The detection footprint for terrestrial transmitters from the ISS is thus a traveling circle 370 km in diameter centered under the satellite. This circle will, at its maximum diameter, pass over an animal transmitter in about 45 seconds or in enough time for about 22 pulses for a transmitter pulse interval of two seconds. The pass-over time will be less for off-center passes. For instance, if the satellite's closest approach is 130 km, the time to detect a transmitter signal will be reduced to 31 seconds or just enough time for about 15 pulses. At 160 km off-center, the time allowed to detect a transmitter signal drops to about 22 seconds (11 pulses). Taking 11 pulses as a minimum for reliable detection we thus have the satellite sweeping a 320 km wide path. Such a path is covered at least every five days. Thus, in the above example, a receiver installed at the ISS will detect a songbird fitted with a transmitter approximately 1.5 times per week.

The number of pulses that are detected by the ISS-receiver is thus a crude measure of how far off to the side the animal is. Subsequent passes could be used to resolve the to-the-left versus to-the-right ambiguity. The time of the middle-of-the-set pulses is a measure of closest approach. These crude measures will allow closer estimation of position, perhaps to a radius of 40 km.

An even higher accuracy can be attained if more than one antenna can be installed at the ISS. Higher-directivity receiver antennas would improve performance by providing stronger signals. An additional advantage of a smaller footprint would also be that less man-made noise is received. The smaller footprint also reduces the width of the path swept and the number of pulses per pass. However, the small size of a footprint could easily be increased if five separate receivers, each with a higher-directivity antenna, were installed. Each antenna would provide near ideal, improved signals, more accurate locations, and less noise without reducing total footprint size. Once birds are located from space within a circle of 40 km they could, if desired, be searched for by ground-tracking vehicles or small planes, which is routinely done in terrestrial radio-tracking.

Which transmitter frequency should be used?

The frequency should be chosen to reduce interference from earth transmitters and gadgetry as much as possible. Observations while tracking animals from airplanes over the midwestern United States show that frequencies in the 150 to 170 MHz band are heavily used, as are all the television frequencies (170-213 and 480 and up) and the mobile services in the 450-470 MHz band. The frequencies from 300 to 390 MHz are rapidly becoming polluted with illegal garage door superegnerative receivers and "wireless" household light and coffee-maker controllers.

Although the proposed space tracking would provide relatively poor location accuracy by terrestrial standards, we suggest that the advantages of studying the connectivity between breeding and wintering grounds in songbirds would outweigh such shortcomings. In addition, space tracking of songbirds would allow us to investigate long-distance dispersal phenomena that are currently largely beyond scientific reach (but see Winkler, this volume).

Future directions

Our long-term data combined with modern eco-physiological methods suggest that a detailed mechanistic understanding of individual migratory behavior of wild songbirds can be achieved. Many important questions could be addressed in the future: (1) How representative are *Catharus* thrushes for New World migrating songbirds? Are decision rules likely to apply generally across taxa and in other migration systems? How and when might they differ? The development of automated radiotelemetry systems (ARTS)(Cochran et al. 1965; Wikelski and Kays 2003) allows for the continuous monitoring of tens of individuals per stopover site. Many additional migrant species could be radio-tagged and followed during stopover and migration. (2) How representative are our data for migratory behavior of *Catharus* thrushes elsewhere and at other times during their migration? Again, ARTS systems established at several areas along the migration routes of thrushes would provide information about the within-species variability in migration tactics. In particular, more information is needed how migration tactics change when large geographical barriers such as deserts or water need to be overflown. A comparison of data from overland migration flights in the New World with data on the crossing of ecological barriers in the Old World could be very informative. Migration tactics in the New World could conceivably differ from those in the Old World in many ways, in particular because of large ecological barriers (Sahara, Alps,

Mediterranean) that exist in Europe and Africa. It is therefore possible that optimization criteria for overland migrants (our study) with regard to fat deposition, digestion, and speed of migration are different from birds that repeatedly have to cross ecological barriers. (3) How do birds adjust their in-flight behavior to atmospheric conditions? Modern atmospheric simulation models could be combined with in-flight heart rate, wing beat, and respiration measurements, with simultaneous determinations of the birds' flight altitude. We hypothesize that changes in physiological parameters should be closely tied to local atmospheric conditions. We also expect birds to adjust their altitude to get into different ambient temperatures. (4) What are the behavioral and physiological mechanisms that allow migrating songbirds to find their way from breeding to wintering grounds? The establishment of a receiver setup at the International Space Station will allow us to conduct orientation experiments on a grand scale in the wild. Birds could be relocated during their migration and the outcome of such manipulations could be followed on intercontinental scales. Along the same lines, one could conduct clock-shift experiments on circannual clocks and determine how important such seasonal cues are in the wild. (5) Where do conservation-relevant migrant songbird species go when they disappear from the north-temperate map? For many species such as the European Aquatic Warbler (*Acrocephalus paludicola*) or even common birds like the House Martin (*Delichon urbica*), it would be very important to identify major wintering sites. In general, achieving connectivity between breeding and wintering grounds in songbirds would solve many long-standing mysteries of bird migration that cannot be addressed with current methodologies.