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New technologies for monitoring bird migration and behaviour

WOLFGANG FIEDLER*
Vogelwarte Radolfzell, Max Planck Institute for Ornithology, Schlossallee 2, D-78315 Radolfzell, Germany

Bird ringing and other tracking technologies have the potential to be equal partners in ornithology, with the former being ideal for broad, large-sample-size approaches and the latter being more suitable for focused studies in much greater detail. Bird tracking methods such as radio tracking, satellite tracking, geolocator loggers, passive integrated transponders or even the use of the worldwide mobile phone network for animal tracking are rapidly evolving and offer high spatial and temporal resolution for following bird movements. However, there are still limitations in equipment size and costs as well as in long-term data management which is still far from the highly standardised database system established for bird ringing data. Ornithology and conservation profit considerably from the existence of these individual marking and tracking methods as part of a common toolbox from where the most suitable tools or combination of tools may be selected to address important scientific questions.

The German ornithologist Johannes Thienemann closed the main part of his 1927 book *Rossitten*, covering the migration of birds there, with a chapter 'Thoughts about modern bird migration research' and wrote 'The local observer is too much bound to the clod, to space and to time but birds are the most agile creatures. Always he wants to follow them into the distance. But don't at this point the wishes of the bird migration researcher meet with today's whole pursuits? Isn't technology just now about to overcome space and time? And shouldn't that be a benefit for science within a reasonable time? All the great new achievements of technology: radio, telephone, automobile, airship, could have been especially commissioned to bird migration research [...]! I often say that the solution of many a riddle in bird migration is actually only a question of money, just as with so many other things in life, too.' (Thienemann 1927; translation by the author). At that time it was 24 years since Thienemann had started the 'bird ringing experiment' at an institutional level and in his further thoughts about the use of new technologies he added bird ringing to the list.

Today, another 82 years later, in the face of satellites observing every square metre of earth, constantly manned laboratories in space and a breathtaking miniaturisation of electronic devices, the thoughts of the old father of bird ringing are not out of date – and neither is the technique of bird ringing. There are many examples where results from bird ringing in connection with in-depth approaches with more modern technologies have led to amazing results and many more are to be expected for the future. This means that bird ringing and other bird-tracking technologies have the potential to be equal partners in ornithology, with the former being ideal for broad-scale approaches with large sample sizes and the latter being more suitable for narrower studies in much greater detail.

* Email: fiedler@orn.mpg.de

TECHNOLOGIES

Radio tracking

Radio tracking is the localisation of a device sending a radio signal by a receiving device. The sending device can be fixed on an animal in the form of a small tag which sends pulsed electronic radio signals. The receiver, in combination with a directional antenna is used to find the direction from which the signal comes. While the directional information can be very accurate, the distance to the sender (the tagged bird) is not. Therefore, it is necessary either to approach the sender as closely as possible by following the detected direction or bearing to get a good localisation ('homing in') or by direction finding at the same time from two different places with the correct localisation determined by the intersection of both bearings (triangulation). Today it is possible to radio track from the ground or from an aircraft and it can be done manually or by automated devices with several linked antennae and a processing unit that calculates the position of the sender from the strength of signals arriving at the different antennae. Sometimes simple tracking is also called telemetry, but this term should be reserved for those cases where not only position but also other data, such as heart rate or body temperature, are remotely sampled and sent by radio waves to a receiver.

Today, the smallest sending units are light enough to be glued onto honey bees (Roach 2008). As a commonly acknowledged rule, to avoid artefacts through abnormal behaviour, increased energy demands or reduced manoeuvrability, a flying animal should not be equipped with an additional load exceeding 5% (3%–5% for birds in Britain & Ireland) of the body mass (Caccamise & Hedin 1985). This means that, depending on the size of the bird and the programmed duty cycles of the sender, these units can send for a few days only or up to several years. The range is normally restricted to a few hundred metres up to more than 10 km. This technique is used widely to explore home ranges, feeding grounds or shorter dispersal flights of birds but researchers have rarely succeeded in following individual birds on real migration using this technique (Bowlin *et al* 2005). However, recent studies on New World *Catharus* thushes represent a landmark in bird migration research, since it was possible for the first time to follow Swainson's Thrushes *C. ustulatus* and Hermit Thrushes *C. guttatus* on active migration flight (Bowlin *et al* 2005). Using biotelemetry, it was possible to record decisions about the length of each leg of the journey, route and wind compensation; furthermore, energy consumption could be estimated because birds could be recovered after the end of a nightly flight (for more details see Cochran & Wikelski 2005).

Satellite tracking

In satellite tracking technology, the sender is tracked from space by satellite. It is evident that this enables us to follow birds over much larger distances. Currently, the most widespread system is maintained by the company Argos which has five satellites circling the earth on polar orbits at an altitude of 850 km (www.argos-system.org). One way of localisation is Doppler technology, where the sender produces an identification signal which, due to the Doppler effect, changes when the satellite either approaches the sender or is veering away from it. This technique provides two pairs of geographical coordinates where one pair is correct (with a certain error boundary) and the other is wrong. Judgement about which is the correct pair of coordinates is mainly the observer's decision and more objective approaches are still technically challenging. Furthermore, the technically-achievable density and accuracy of data are hardly ever met and accuracies of not more than several dozen kilometres are the rule.

Advanced satellite tracking systems make use of another satellite-based localisation tool which we today commonly use in our own navigation devices: the global positioning system (GPS). With this system, devices try to find a series of satellites with known positions above earth and calculate their own position by comparing the relative power of the signals emitted by these satellites. Devices currently of the size of a small pocket lighter can be used on birds and can calculate their local position the same way and send the results through the Argos satellites to a ground station. This increases the accuracy of localisations remarkably and makes it possible, for example, to locate nests or roosting trees of birds reliably from the received data.

Some of the most fascinating long-term journeys of birds have been demonstrated through satellite tracking. The current record-holder is the Eastern Bar-tailed Godwit *Limosa lapponica baueri* female 'E7' that showed an 11,500-km flight right across the Pacific Ocean from Alaska to New Zealand. The same bird had been tracked the previous spring crossing the Yellow Sea to China (10,000 km) and then proceeding another 5,000 km to the breeding grounds in Alaska (Gill *et al* 2009). Also, many seabirds have been followed on their journeys over the world's oceans, including nesting albatrosses foraging over distances of thousands of kilometres (Birdlife International 2004, Pinaud & Weimerskirch 2007).

When tags are solar powered they have the potential to operate and give useful data as long as the bird lives. This has enabled us to follow individual birds over several migration periods and identify individual decisions and flexibility in migration habits over many years. For example, nine complete journeys of the female White Stork *Ciconia ciconia* 'Princess' have been tracked between the eastern German breeding grounds and the African wintering areas during the period 1994–2006 (Berthold *et al* 2004, www.prinzesschen.de). Furthermore, satellite tracking helps to identify migration corridors and wintering grounds where ring-recovery probabilities are low. It was very surprising when the satellite-tracked White Storks from eastern Germany and Poland headed to their first important wintering site in the area east of Lake Chad and in western Sudan. Ring recoveries, although numerous in this species even from the wintering grounds, had not revealed the importance of this area as an early-winter staging region because people there did not report stork rings (Berthold *et al* 2001).

During the last 20 years, the satellite tracking of birds has brought many key insights into migration behaviour and the identification of wintering or breeding areas. Some studies have not tracked the natural behaviour of birds but have observed experimentally manipulated birds. In this way, the results from laboratory experiments can be evaluated by transferring individuals into natural conditions while keeping sample sizes to a realistic level. When Thienemann wanted to test the orientation of juvenile White Storks by the delayed release of individuals, he had to rely on resightings of ringed and colour-marked individuals and received only 12 recoveries from 197 released birds (Schüz

1951). A comparable experiment with greater data output was recently repeated using only 10 White Storks equipped with satellite transmitters (Chernetsov *et al* 2004).

The most obvious limitation to this technique, besides the high costs of the tags and satellite use, is currently the size of the transmitters, which do not allow a bird lighter than 100 g in body mass to be tracked (5 g transmitter, Meyburg & Meyburg 2008, www.raptor-research.de).

Geolocator loggers

Loggers are devices that store data on a memory unit until it is read out by an external reading unit. Animals can be tracked by logging data from various kinds of sensors attached to the loggers. Ideally, for tracking an animal, GPS coordinates are taken at pre-programmed times and logged to the memory of the device. In cases where these GPS units are too large for the size of bird, geographic information can be calculated from much smaller devices designed to record the time of dawn and dusk. A photoreceptor coupled with an accurate clock can help to calculate latitude from the duration of daylight and longitude from the time of sunrise and sunset. Very recently, this has permitted the first long-distance tracks of migrating songbirds (Stutchbury *et al* 2009). An alternative approach logs data from an attached compass which can later enable researchers to calculate migration routes. This method has been used to track seabirds such as Brünnich's Guillemot *Uria lomvia* (Falk *et al* 2001). However, it requires a considerable amount of additional knowledge and assumptions, such as wind speed and direction, to interpret the data.

While loggers save weight and energy compared to long-distance sending units, they add some vulnerability to the studies as they need to be found again to read out the data. Therefore logger technology is widely used in seabirds and other large birds that return to the same breeding places for many years where they can be retrapped. It is especially the need for retrapping the individual that is the major obstacle for a wider use of this technology. This is why more-recent loggers have been designed to incorporate sending units that enable users to establish a radio link between a receiver and the logger on the bird over a distance of up to 5 km. The next generation of these radiolink loggers is currently being developed and will be available with an interface for various sensors (heart rate, body temperature, salinity, camera, microphone and many others) that will add additional information to GPS geolocation data (M. Wikelski, pers comm). Already, loggers of these types have enabled us to receive positioning data with a high spatial and temporal resolution which is not possible to collect by manual ground tracking. For example, they have been used to track Trumpeter Hornbills *Ceratogymna bucinator* for several weeks in fragmented South African landscapes, with a 15-minute resolution and an accuracy of a few centimetres to a few metres, in a project to understand the importance of this species as a seed disperser (Böhning-Gaese *et al* in preparation).

Passive Integrated Transponders (PIT) tags

PIT tags use Radio Frequency Identification (RFID) technology. From the entire list of devices treated in this review the PIT tag is probably the closest relative to the traditional bird ring. It does not have its own power or memory and simply gives an identification number when it is read out. When reading a PIT, a low-frequency radio wave is sent to it by a scanner (transceiver) which delivers the energy for the tag to send back an identification code. This method is widely used for marking pets and zoo animals where these transponders are encapsulated in a rice-grain-sized piece of glass and implanted under the skin or in a body cavity. Since the tag is very difficult to extract from a live animal, this technique provides good protection against illegal animal trade and theft. In studies of wild birds, PIT tags are either implanted or attached to a leg ring. Birds then can be identified automatically each time they approach an antenna at a feeder, a balance or a nest box. It is obvious that PIT tags will not be suitable to replace bird rings entirely since the tag is not visible to an observer and it can be read only with special equipment – both these factors make it impossible to receive a foreign recovery of a marked bird.

The strength of RFID technology clearly is the potential for automated recognition of birds, *eg* when they approach or enter a nestbox or a feeder. In a colony of Common Terns *Sterna hirundo* in northern Germany, individual behaviour and the physiological condition of birds carrying PIT tags have been followed over many years because their presence in the colony can be recognised by an automated recording system and even their body weight can be taken when they roost on one of the poles that are connected to electronic balances (Becker & Wendeln 1997).

With currently-used technologies, the distance between the transceiver and the PIT tag needs to be less than a metre. While this is sufficient for detecting a bird in a nestbox, it is not possible to detect the presence or absence of a PIT-tagged individual within a whole home range. New RFID tags working in the ultra-high frequency band will allow reading distances up to 100 m. They have been developed mainly for consumer logistics and security purposes (*eg* to identify the RFID-tagged content of a shopping trolley when moving through the exit) and therefore it can be expected that we are, currently, only at the beginning of a trend towards smaller and cheaper tags. The smallest RFID tags currently available are 0.05 x 0.05 mm in size (BBC 2007) but they need an external antenna to work which is 80 times bigger than the tags. Also, RFID tags now can be equipped with their own power supply and memory capacity. Thus, they can be linked to sensors and GPS modules and send not only their identification signal but also additional data. This makes them, in principle, similar to the loggers described above.

Global System for Mobile Communication (GSM) tracking

Everyone who uses a mobile phone is linked to the GSM and can be located through the antenna network. The system that is used by the police to find people carrying a mobile phone can, of course, also be used for animal tracking when the animal is equipped with a GSM unit that communicates with the worldwide infrastructure for mobile communication. Furthermore, the GSM unit can be coupled with sensors and GPS modules and thus can send coordinates and other data through the GSM system directly to the mobile phone of a researcher. Finally, in contrast to all other devices described here it will be possible, in the future, to communicate with the tag on the bird and change settings of the sensors, such as switching them on and off, or even manipulate a bird experimentally. GSM tags for tracking animals (including larger birds) have been developed and will be available soon (Kays & Wikelski 2007). As in other devices, the biggest challenges are reduction of size and power consumption.

LIMITS AND SOLUTIONS

Currently there is no long-distance tracking device available for the largest group of birds of interest to ornithologists – the medium-sized and small songbirds. Although the miniaturisation of devices will continue, it is not certain that the current arsenal will enable us to track, for example, a tiny Willow Warbler to Africa and back. The 'International Cooperation for Animal Research Using Space' (ICARUS) initiative aims to develop a worldwide platform for tracking small animals based on a space device (Wikelski *et al* 2007; www.icarusinitiative.org). The idea is to be able to track, from space, miniature radio transmitters weighing less than a gram which are already available. This should be technically achievable and the dream of closely following a hummingbird while it crosses the Gulf of Mexico or a Wheatear on its way from Siberia to western Africa and back might come true, if politicians and space agencies acknowledge the value of such a system for understanding animal migration.

Besides the technical limits described above, costs also limit the use of these new technologies. Achieving a considerable sample size for gaining more than anecdotal evidence for movements rapidly increases the required budget to many thousands of Euros. Together with potential animal or device failures these costs assign a high risk to such studies which can be covered only by large, well-funded institutions. The gathering of long-term data sets on population monitoring, survival or changes in migration behaviour using these technologies will blow a massive hole through even the richest science budgets: therefore the low-cost method of bird ringing remains an emancipated tool even in the modern list of animal-marking methods. This is even more true when it is remembered that a vast element of bird ringing is based on volunteer work (Baillie *et al* 2007) while high cost largely restricts other tracking technologies to institutions or rich foundations employing professional researchers.

While the technology is developing rapidly, the management, storage, presentation and quality standardisation of data are lagging behind. For example, most papers presenting satellite-tracking data are accepted without providing any information about localisation accuracy, which in many cases can be presumed to be much lower than the dots on high-resolution maps might imply. Sometimes, even, the required standards of scientific accuracy take a back seat behind enthusiasm over technical achievements.

One of the big achievements of the bird ringing system is the potential for multiple usage of data. These data are not only used for analyses by the person who collected them but also, as a matter of course, go into databases where they are ready for any subsequent analyses. This requires certain standards in data storage and coding to make data available in a comparable and understandable way, as has been achieved in the transfer of ringing data to the international EURING Data Bank (Baillie *et al* 2007). The tracking devices described here can produce massive amounts of data and, currently, there is no standard on how and where they can be stored in a format that future generations will be able to understand and use. One approach to overcome this problem is the Movebank initiative (www.movebank.org) where all the various types of tracking data can be stored for the long term and where tools for handling, analysing and visualising these data are developed and offered.

A common problem of all electronic tracking devices, as well as bird rings, is the need for an initial capture of the individual bird. The more expensive the equipment the greater the disincentive to attach it to nestlings, which, although they may be easily accessible, have a high mortality, but to attach devices to adult birds which have a much higher survival probability but often a much lower accessibility. At this point, at least, many studies rely on the experience of skilled bird ringers.

FUTURE PERSPECTIVES

Although new technological achievements make it possible to fill gaps in knowledge that can never be filled by bird ringing (Cooke *et al* 2004, Kays & Wikelski 2007) it is unlikely that they will fully replace conventional bird ringing. The system, with tens of thousands of volunteer bird ringers, many with a lifetime of experience with 'their' bird species, cooperating ringing schemes and a high level of standardisation as well as constantly developing improvements in data quality and analysis tools, is unlikely ever to be completely superseded by tinier and tinier electronic devices. Ornithology and conservation will profit most from a peaceful coexistence of all these individual marking and tracking methods in a common toolbox from where the most suitable tool may be chosen for each scientific question. While some individual birds with tiny electronic devices will provide us with currently-inconceivable details of their lives, others will just be recognised individually by their leg ring or colour mark to supply data for broad-scale approaches such as population monitoring or other studies that need large sample sizes. Volunteer bird ringers will continue to work on these projects; they will also be needed to help researchers to equip birds with electronic devices in larger numbers and they will continue to contribute their immense knowledge about birds to the ornithological community.

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