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IN PURSUIT OF WILD JOURNEYS: TRACKING LONG DISTANCE BIRD MIGRANTS
조류의 장거리 이동 추적: 야생의 여정을 따라

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Abstract

A number of possibilities exist for tracking the sometimes even global journeys undertaken by migrating birds. Birds fitted with radio transmitters can either be located from the ground or from aircraft (conventional satellite tracking), or from space. Alternatively, positional information obtained by onboard equipment (e.g. GPS units) can be transmitted to receivers in space. Using these tracking methods has provided biologists with a wealth of insight into the migration routes, stopovers and other behaviours in long-distance migrants that are otherwise very difficult to follow. This knowledge has important implications for e.g. conservation and understanding disease transmission and effects of climate change. The weight of satellite radio transmitters complicates study of the majority of bird species, but the weight is likely to be greatly reduced in the near future.

요 약

철새가 비록 전 지구를 누비며 이동한다 해도 때로는 이들을 추적하기 위한 여러 가지 방법이 존재한다. 전파 발신기가 부착된 조류는 지상, 공중(재래식 인공위성 추적) 또는 대기권 밖에서 직접 위치를 추적할 수 있다. 또 다른 방법으로서, GPS 수신기와 같이 추적기 내부에 장착된 장치에 의해 얻어진 위치 정보가 우주에 있는 수신기로 전송될 수도 있다. 이런 추적 방법들은 생

물학자들에게 직접 추적하기 어렵고 장거리를 이동하는 철새들의 이동 경로, 중간 기착지 및 기타 행동에 대한 풍부한 정보를 제공해 준다. 이러한 지식은 종의 보전이나 질병 전파의 이해, 기후 변화의 효과 판단 등에 중요하게 활용될 수 있다. 인공위성 추적 장치는 무거운 중량으로 인해 조류 중 대부분의 종에서 연구에서 적용하기 어렵지만, 그 무게는 가까운 미래에 크게 감소될 수 있을 것으로 보인다.

Introduction

Bird migration is among the most fascinating natural phenomena. And the journeys undertaken by some of the billions of migrating birds that travel thousands of kilometres (Fig. 1) each year are truly fantastic: Arctic terns commute between the poles, sooty shearwaters travel up to 65,000 km annually on their migration between breeding areas in New Zealand and wintering area in the North Pacific, and wandering albatrosses may travel 2/3 of the distance to the moon before they even start to breed. Less well known are the travels by smaller terrestrial land birds, but in the willow warbler individuals breeding in eastern Siberia are thought to travel up to 15,000 km to their wintering grounds in Africa. Measured in body lengths, this feat constitutes the longest migration in any animal.

Human interest in the subject can be tracked even back to Aristotle, who speculated about the seasonally changing avifauna. Among his more imaginative explanations were that some birds travelled to the moon and some simply became different species, like the cuckoo in the summer that became the sparrowhawk in the winter. Among other ideas was the possibility that birds hibernated on the bottom of lakes. Even up until the late 19th century, several attempts were made to try to find hibernating birds and to investigate whether birds were able to breathe under water, by submerging them for prolonged periods (!). Finally, in the early 20th century ring recoveries documented long-distance migrations of e.g. white storks to

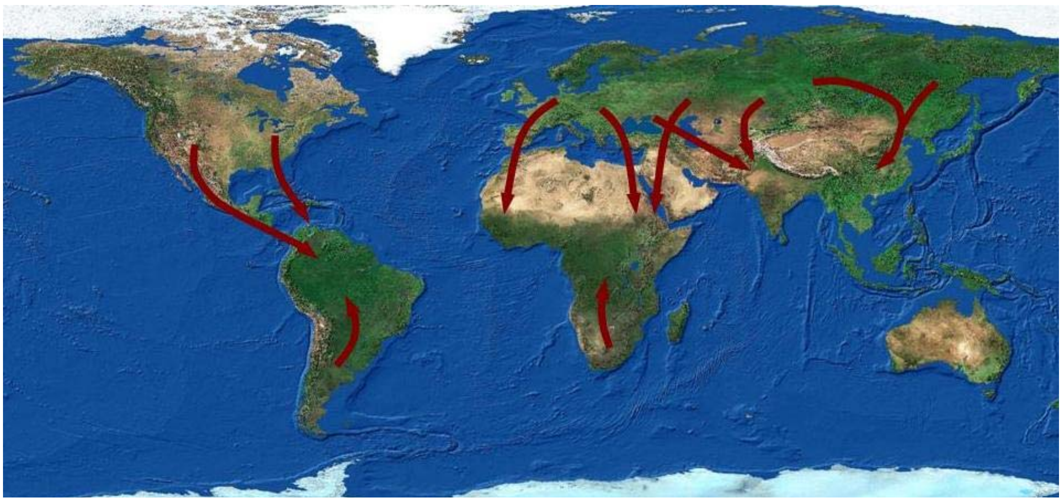

Figure 1. Examples of routes used by migrating birds.

Africa.

Migration is a very important ecological phenomenon, and a better understanding is crucial in e.g. issues of conservation, disease transmission and agricultural pests.

Tracking individual migrants

The early methods for studying migration all suffered from the problem that individuals could not be followed for longer periods of time. Thus, understanding of migration had to be based on combining observations from several different sites dispersed in space and often time into an overall picture. However, methods based on radio telemetry and data loggers now enable us to follow individual migrants over longer time periods.

In methods based on radio telemetry, the bird is fitted with a small device emitting a radio signal that can be directly used to locate the animal and determine its position. The receiver and antenna can either be situated on or near the ground (Conventional radio telemetry), e.g. handheld, in a car or in an aircraft, or it can be in space (Satellite telemetry).

In data loggers, the device fitted to the bird contains an onboard unit that can be used to determine the position. This information is then stored and can later be downloaded. In most applications, this position determination has used either simple recording of transitions between night and day or the very precise GPS (Global Positioning System). The problem is that one needs to recover the device to download the data. Many breeding birds return to the same nesting site and can then be trapped again, but this is generally difficult, if one wants to study e.g. the migrations of inexperienced migrants. The newest methods allow a combination of data loggers and satellite telemetry, with the bird's position determined using GPS and then transmitted to a satellite for download.

However, as a general rule bird cannot carry more than 2-5 % of their body weight extra without significant consequences for their behaviour. This greatly restricts the possibilities for using radio transmitters because long range transmission comes on the cost of higher weight. Currently, the smallest transmitters that can transmit to a satellite weigh around 9 grams (see e.g. www.microwavetelemetry.com), while the smallest GPS units with the capability of downloading positions via satellite weigh down to 22 grams. However, the smallest 9 grams transmitters are still to large for about 80 % of the world's bird species.

Conventional radio tracking

Transmitters with weights down to below 0.5 grams can be successfully tracked with conventional radio telemetry. This means that almost all the world's bird species can be tracked with this method. However, the detection range of these small transmitters is typically relatively short (less than 20 km in unobstructed view) and this make the use of these for tracking migrating birds difficult and time consuming. The most effective method for smaller bird migrants is to follow these from aircraft, often in combination with tracking from vehicles on the ground. This method was introduced by Bill Cochran already in the 1960s, and in 1987 Cochran published the so far longest tracking of a migrating songbird, a Swainson's thrush followed for 6 days over more than 1,500 km (Fig. 2).

This method has additionally proved very useful in the study of migratory orientation

Figure 2. The track of a Swainson's thrush followed for 6 days over more than 1500 km through the Midwest of USA.

and physiology. Studies manipulating the magnetic field have shown how migratory thrushes use the sunset to calibrate their magnetic compass (Cochran et al. 2004) and the study of the compasses in the wild greatly helped understanding results obtained in laboratory conditions. Other studies have enabled calculation of total energy expenditure during migration and detailed description of flight during migration.

With some prior knowledge of the migration route, it becomes somewhat easier to follow migrants with conventional radio tracking. Radio transmitters can be located along the route by actively searching at known stopover sites, or by setting up a large-scale receiver "curtain", automated receiver stations that can automatically scan for the particular frequencies, that the birds have to pass on their migration. Such methods have been applied in a number of shorebird species, typically describing general patterns and timing of migration. However, for large-scale description of migration patterns the method is still too labour intensive.

Satellite tracking

Some very impressive migrations have been revealed with the use of satellite tracking. Recently, a satellite tracking of a bar-tailed godwit revealed a most likely non-stop spring migration flight of more than 10 000 km from New Zealand to China (http://www.werc.usgs.gov/sattrack/shorebirds/overall.html)! In addition to giving important information about the birds' flight route and stopovers from little known areas, this impressive travel shows that such birds are able to perform migrations with satellite transmitters.

Today, all satellite transmitters use ARGOS satellites (http://www.cls.fr/html/argos/welcome _en.html). The satellites use the Doppler effect to determine the transmitter's location from changes in received transmitter frequencies during a satellite pass. In general, locations are not very accurate, typically several to many kilometres, but good quality locations are accurate up to 1 kilometre. With a GPS unit added to the transmitter, it is possible to transmit the GPS locations to the user via the ARGOS satellites. In that case, the locations become much more accurate, often within metres of the true location, but these transmitters are also much heavier. Another drawback with the ARGOS transmitters is the very high cost. Typical costs for a satellite telemetry study are more than $5,000 per individual!

Studies using satellite tracking

Despite the high costs and limited number of species that can be tracked using satellite telemetry, there has been a wealth of studies on long-distance migrants. Satellite tracking has revealed detailed migration routes in, among others, storks; wildfowl like swans, geese and ducks; raptors, cranes, bustards and a few of the largest wader species. Additionally, satellite tracking has been used to study other behaviours, as e.g. night flight in frigatebirds, but it has also revealed long-distance movements in nomadic species. A snowy owl breeding in Canada has been shown to move almost 2,000 km to breed in eastern Siberia in a later year.

Though most of the studies have been undertaken in the western world, there have been studies on all continents. Satellite tracking studies of e.g. storks, geese, raptors and cranes have revealed migration routes and stopover sites important for conservation all over the world, but not least in parts of the worlds where migration patterns are relatively poorly known, as e.g. Asia. Tracking of a number of individuals of a few raptor species have allowed comparisons across species and among sex and age classes (Fig. 3). The smallest species that is currently being tracked is the hobby, and these small falcons are currently being followed on their long

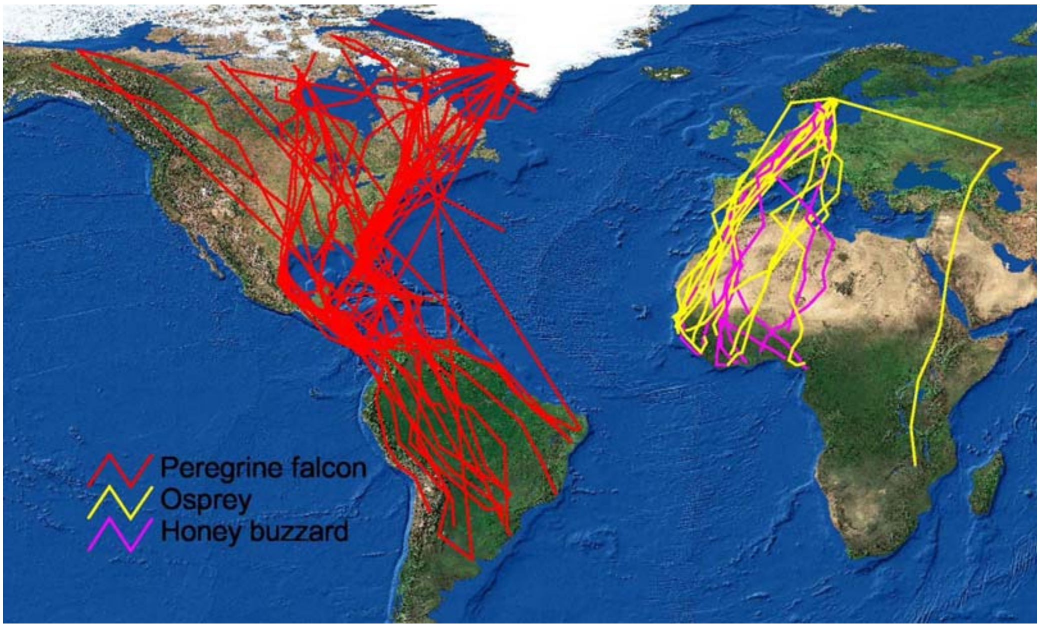

Figure 3. Movements of raptors tracked by satellite telemetry (Track data from Fuller et al. 1998, Hake et al. 2001, 2003 and Kjellén et al. 2001).

Figure 4. GPS positions of an osprey travelling through Denmark on its way to breeding grounds in Sweden (Courtesy of M. Hake, R. Strandberg, R. Klaassen, and T. Alerstam).

migrations from southern Sweden to southern Africa.

Only recently have the weight of the more accurate GPS transmitters decreased so much that they can be used on long-distance migrants. With GPS transmitters, one gets a very accurate picture of the migration, as e.g. shown by the migration through Denmark by a Swedish osprey (Fig. 4). The bird left Denmark at the northernmost point, a famous migration hotspot, Skagen, where it was noted by amateur ornithologists counting migrating birds without them taking notice of the transmitter!

So far, most of the studies have been somewhat descriptive in their nature. Recently, a number of satellite tracking studies have aimed at understanding the behaviours underlying the observed tracks. Examples of results from such studies include studies showing: that adult raptors compensate for wind drift while juveniles do not, that travel decisions in ospreys are almost unaffected by weather and that the magnetic compass does not seem to provide the primary guidance in migrating raptors. In only a single study has actual experiments been performed: Chernetsov and co-authors (2003) satellite tracked displaced and delayed white storks, similar to earlier studies with ringed birds.

Outlook

It has now become clear that the possibility of tracking even small songbirds from space is potentially possible with current technologies. The ICARUS initiative (International Cooperation of Animal Research Using Space) is working towards establishing a remote sensing platform that can track radio transmitters as small as 0.3g. The high costs of launching a satellite or alternatively placing an antenna on an existing satellite dedicated to this purpose continue to be a main hurdle, and the main task in the near future will be to convince funding bodies or space agencies about the importance of the system. The ICARUS initiative and its progress can be tracked via the homepage (www.IcarusInitiative.org).

ARGOS satellite transmitters are continuously being reduced in weight, but much more than a 50 % reduction within the next five years is probably not realistic. Currently, the DTUsat (www.dtusat.dtu.dk) is the only project in the physical process of constructing a satellite that hopefully will enable a reduction of satellite transmitters. The goal of DTUsat is to be able to receive accurate GPS positions from 5g transmitters. A number of other initiatives work towards the same goal of being able to download locations from GPS units, e.g. via the GSM net used for cell phones.

With the current interest and engagement in satellite tracking of birds, the task of being able find the needle in the haystack: to track even the smallest bird species on global migrations, will no doubt become reality within the next 10-15 years.

References

Chernetsov N, Berthold P, Querner U, 2004. Migratory orientation of first-year white storks (*Ciconia ciconia*): inherited information and social interactions. Journal of Experimental Biology 207, 937-943.

Cochran WW, 1987. Orientation and other behaviours of a Swainson's thrush followed for 1500 km. Animal Behaviour 35, 927-929.

Cochran WW, Mouritsen H, Wikelski M, 2004. Migrating songbirds recalibrate their magnetic compass daily from twilight cues. Science 304, 405-408.

Fuller MR, Seegar WS, Schueck LS, 1998. Routes and travel rates of migrating Peregrine Falcons *Falco peregrinus* and Swainson's Hawks *Buteo swainsoni* in the Western Hemisphere. Journal of Avian Biology 29, 433-440.

Hake M, Kjellén N, Alerstam T, 2001. Satellite tracking of Swedish ospreys *Pandion haliaetus*, autumn migration routes and orientation. Journal of Avian Biology 32, 47-56.

Hake M, Kjellén N, Alerstam T, 2003. Age-dependent migration strategy in honey buzzards *Pernis apivorus* tracked by satellite. Oikos, 103, 385-396.

Kjellén N, Hake M, Alerstam T, 2001. Timing and speed of migration in male, female and juvenile ospreys *Pandion haliaetus* between Sweden and Africa as revealed by field observation, radar and satellite tracking. Journal of Avian Biology 32, 57-67.

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■ 주요 경력 및 관심 분야 *Experience Summary and Ornithological Interests*:

코펜하겐 대학교 동물학 박물관에서 조류의 이동에 대한 연구로 박사 학위를 받았다. 덴마크 연구 위원회(Danish Research Council)로부터 박사 후 연수 지원을 받아 프린스턴 대학(Princeton University)에서 연구원(research associate)으로 근무하였으며, 현재 코펜하겐 대학교의 코펜하겐 조류 가락지 부착 조사 센터(Copenhagen Bird Ringing Centre)를 이끌고 있다. 프린스턴 대학의 Martin Wikelski 박사, 룬트 대학교(Lund University)의 Thomas Alerstam 박사, 코펜하겐 대학교의 Carsten Rahbek 박사 등과 함께 대부분 조류의 이동과 귀소 능력에 대한 광범위한 연구를 수행해 왔으며, 부분적으로는 박쥐의 방향 탐지 능력과 멸종 위기에 처한 덴마크의 금눈쇠올빼미(little owls) 개체군의 생태에 대한 연구도 진행하고 있다. 주요 연구 방법은 재래식 무선 추적과 인공위성 추적이지만, 조류의 이동 연구에서 흥미로운 주제를 밝히기 위하여 광범위한 가락지 조사 자료의 분석과 같은 다른 방법도 함께 이용한다.

Kasper Thorup has a PhD on bird migration from the Zoological Museum, University of Copenhagen. He has been research associate at Princeton University on a post doctoral fellowship from the Danish Research Council and is now heading the Copenhagen Bird Ringing Centre at University of Copenhagen. He has extensive collaboration with Martin Wikelski, Princeton University, Thomas Alerstam, Lund University and Carsten Rahbek, University of Copenhagen, mostly working on migration and orientation in birds, but he has also worked on orientation in bats and on the biology of the threatened Danish population of little owls. The main method for investigation has been radio tracking, using both conventional and satellite tracking, but other methods including analysis of extensive ringing data sets have also been applied to pursue interesting questions in bird migration research.

■ 주요 저서 및 논문 ***Selected Publications*:**

Bønløkke J, Madsen JJ, Thorup K, Pedersen KT, Bjerrum M, Rahbek R 2006. **The Danish Bird Migration Atlas**. Rhodos Press & Zoological Museum, University of Copenhagen.

Holland RA, Thorup K, Vonhof M, Cochran WW, Wikelski M 2006. Bat orientation using Earth's magnetic field. **Nature** 445, 702.

Thorup K, Rabøl J 2007. Compensatory behaviour following displacement in migratory birds. A meta-analysis of cage-experiments. **Behav Ecol Sociobiol** 61, 825-841.

Thorup K, Alerstam T, Hake M, Kjellén N 2003. Bird orientation: Compensation for wind drift in migrating raptors is age dependent. **Proc Royal Soc, Lond B** [Biology Letters] 270, S8-S11.

Wikelski M, Kays R, Kasdin J, Thorup K, Smith JA, Cochran WW, Swenson GWJr 2007. Going wild: what a global small-animal tracking system could do for experimental biologists. **J Exp Biol** 210, 181-186.