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First deployment of IoT tracking devices on Common swift *Apus apus*: a pilot study

Michelangelo Morganti[1,2]*, Milo Manica[3], Daniela Casola[3], Lorenzo Colombo[3], Alessandra Stocchetti[3], Wolfgang Fiedler[4], Martin Wikelski[4,5], Klaudia Witte[5] & Timm Wild[4]

[1]CNR-IRSA Consiglio Nazionale delle Ricerche – Istituto di Ricerca sulle Acque, sede di Brugherio (MB), Italy
[2]NBFC, National Biodiversity Future Centre, Palermo, Italy
[3]GIO Gruppo Insubrico Ornitologia, Clivio (VA), Italy
[4]Department of Migration, Max Planck Institute of Animal Behaviour, 78315 Radolfzell, Germany
[5]University of Konstanz, Department of Biology, Germany
[6]University of Siegen, Institute of Biology, Germany

*corresponding author: michelangelo.morganti@irsa.cnr.it

MM 0000-0002-8047-0429, MMa: 0000-0003-2927-8471, TW 0000-0002-2906-2892, KW 0000-0002-2812-9936, WF 0000-0003-1082-4161, MW 000-0002-9790-7025

Abstract - Five breeding adults of Common swift *Apus apus* from a north Italian colony were equipped with lightweight (1.2 g) tracking devices based on IoT (Internet of Things) technology, collecting location data and transmitting them through the Sigfox network of base stations. The main novelty is that these devices enable the real-time transmission of locations with no need for re-capturing. The devices were glued to the back feathers, which were to be lost during moult at the latest. The devices transmitted over variable periods (3-25 days, mean ± SD: 9.31 ± 11.8), collecting in total a mean ± SD of 17.58 ± 18.4 locations per individual. These data mostly recorded movements around the colony, except for one bird that migrated immediately after tagging. This bird was successfully tracked until reaching southern Spain, where transmissions ended because the IoT network is not available out of continental Europe, with a few exceptions. This pilot study demonstrates that swifts can be successfully tagged with lightweight devices without harnessing. While single-direction migration displacements can be successfully tracked over the EU with these devices, researchers need improvements in both the location quality of the Sigfox IoT network and the life length of the devices if they aim to study the details of foraging movements. Eventually, we stress that beyond pure research purposes, tracking swifts through IoT devices—which transmit real-time data to the Animal Tracker mobile app—may also effectively engage the public and enhance conservation awareness.

Keywords: *Apus apus*, bio-logging, movement ecology, IoT devices, tracking

INTRODUCTION

Animal movements have long been a focal point in ecology. Over the past two decades, advances in technology and analytical methods have significantly expanded this interest within research communities, leading to this period being evocatively termed the 'movement ecology era' (Nathan et al. 2008, Kays et al. 2015). Swifts (genus *Apus*) have been the subject of various research efforts due to their unique lifestyle, with an extreme proportion of time spent in flight, only landing during reproduction (Liechti et al. 2013, Hedenström et al. 2016, Wellbrock et al. 2017). Due to this interest, swifts' behaviour has been studied through a variety of techniques, such as acoustic loggers (Amichai & Kronfeld-Schor 2019), radars (e.g. Dokter et al. 2013; Nilsson et al. 2019 among the many papers with this approach) and, only recently, individual tracking devices. Researchers deployed various devices on these species since the first individual tracking of swifts (Åkesson et al. 2012). Most of them were 'GLS' ('Global Location Sensor' or 'light level geolocators'; see Morganti et al. 2018 for a review) and, more recently, GPS (Global Positioning System) loggers (e.g. Hufkens et al. 2023) and ATLAS radio-transmitters (a sort of reverse GPS-like system, see Bloch et al. 2024). Both GLS and GPS loggers can be equipped with other sensors, thus becoming multi-sensor tracking devices able to explore flight patterns when carrying accelerometers (e.g. Meier et al. 2018; Hedenström et al. 2019) and/or altitude patterns if fitted with a barometer (Hedenström et al. 2022, Hufkens et al. 2023).

The majority of tracking data have been used to explore migration timing, migration tracks, location and size of wintering ranges and vertical movements during the reproduction. This hold for Common Swifts *Apus apus (*Åkesson et al. 2012; Klaassen et al. 2014; Hedenström et al. 2016; Wellbrock et al. 2017), *Apus apus pekinensis* (Huang et al. 2021; Zhao et al. 2022), Pallid Swifts *Apus pallidus (*Norevik et al. 2019; Hedenström et al. 2019) and Alpine Swifts *Tachymarptis melba (*Liechti et al. 2013, Meier et al. 2018; but see also Hufkens et al. 2023 for a multi-species study). Among Nearctic swifts, tracking data have been published for at least Northern Black Swifts *Cypseloides niger borealis,* for which Hedenström et al. (2022) studied the vertical night movements of the species during reproduction.

A set of fundamental ecological questions remain unsolved even for the most studied swift species (i.e. western European ones), but, noteworthily, the Apodidae family include almost 100 species, with great research potential on movement tracking studies in the years to come. Indeed, this holds for a wide range of small-sized animals, whose tracking is challenging from a technological perspective. So far, developing new animal-borne tracking technologies and lighter devices is among the main objectives of modern movement ecology.

The common aim of the scientific community is to minimize the impact of device deployment, and it is nowadays clear that to reach this goal, species-specific or at least group-specific solutions should be envisaged. It is generally accepted as an ethical threshold that the weight of a tracking device should not exceed 3-5% of the total body weight of the tracked individual. Swifts are relatively small birds, among the smallest non-passerines. The body size of the most common Palaearctic species ranges from about 100 g for the Alpine Swift to around 40 g for Common and Pallid Swifts (Demongin 2016, Morganti et al. 2018). However, other swift species are significantly smaller (e.g., *Apus caffer*: 18-30 g, Demongin 2016; *Apus affinis* mean weight: 25 g, Bloch et al. 2024). These weight ranges require tracking devices to be extremely lightweight, aiming to respect the 3-5% ethical threshold (i.e., 1.2-2 g for a 'mean' swift of 40 g). Moreover, weight is not all. As a finding, a comparative survival analysis, found that tracking devices for any swift species should be designed without the short rigid antenna (i.e. light-stalk) occurring in some models of geolocators, because this has a detrimental effect on survival, despite the weight of the device itself (Morganti et al. 2018). Indeed, flat devices have been proven to not cause negative carry-over effects, even on individuals carrying a tracking device for more than a full year (Wellbrock & Witte 2022). This may be due to the drag produced by the light-stalk, which may have a negligible effect on most birds but becomes significant in swifts due to their highly aerial lifestyle.

However, all the tracking devices used to date on swifts have in common that they require the birds to be recaptured to download the data (but see Bloch et al. 2024). Tracking requires a capture for deployment at least, and a recapture to retrieve the data, thus implying two manipulations. Therefore, a device which does not require the recapture of the bird halves the capture-associated stress. Since swifts are terrestrial only during the breeding period, when they use cavities (either natural or artificial) for nesting, captures are typically realized at nesting colonies. A wide range of artificial structures have been built explicitly for swifts (or originally for other birds) all over Europe (e.g. Ferri 2018) and these are nowadays widely used for research purposes, along with nesting boxes (e.g. Schaub et al. 2016) installed to favour these species. Some of the birds may abandon their nesting sites after manipulation, thus preventing the possibility of recapturing the bird for data downloading during the same season, in case of devices collecting data over a short period (i.e. some days). Additionally, some birds may move to different breeding sites across different years. This change may be due to manipulation stress or to different reasons, but in both cases, movement data stored in (e.g.) a GLS or a GPS-logger gets completely lost in case the birds are not recaptured the following year.

Moreover, it is important to note that even in cohorts of non-deployed swifts, inter-annual return rates (or apparent survival) typically range from 60-75% in the most successful cases (Åkesson et al. 2012; Wellbrock & Witte 2022). However, in the majority of the studied colonies, the return rate is significantly lower, with less than 50% in most studies for both Common and Pallid Swifts (Morganti et al. 2018). So far, in studies relying on inter-annual recapture of birds, it must be assumed that a considerable proportion of devices are lost. The advantage of receiving real-time data is therefore evident, as it could provide valuable insights into mortality locations and rates.

Attention should ultimately be paid not only to the shape and weight of the device itself but also to the method of attachment, as this can impact the bird's behaviour and survival chances. This concern has sparked debate within the ornithological community, particularly regarding the 'harnessing' deployment method. For example, while ‘leg-loop’ harnessing is perfectly safe for some small insectivorous passerines (e.g. Morganti et al. 2017, McKinlay et al. 2024); backpacks are highly recommended for *Falco* species (Biles et al. 2023). See e.g. Geen et al. (2019) for a comprehensive review of this argument. Overall, it is now accepted that geolocator tagging has a weak negative impact on the apparent survival of small birds, with stronger effects in smaller species and when attached using elastic harnesses (e.g. Brlík et al. 2020). Devices tiny enough to be directly glued on the feathers may have the further advantage of dropping off independently, during body plumage moult. The moult schedule of swifts is characterized by a long duration (6-7 months, e.g., Kiat & Bloch, 2023; Jukema et al., 2015), likely an adaptation to prevent impairments to flight in these highly aerial species. The moult of flight feathers in Common Swifts begins in summer, during breeding, and concludes in their wintering grounds, where body feathers are also moulted (Jukema et al., 2015; Demongin, 2016). Therefore, a device attached to the back feathers of a Common Swifts should remain on the bird throughout fall migration, eventually dropping off in the African wintering areas.

In this contribution, we tested the performance of new-generation tracking devices based on IoT technology (Wild et al. 2023) deployed on Common Swifts breeding in northern Italy. The main novelty of these devices is that they do not require the recapture of tagged birds to obtain the tracking data, nor an external harness for deployment, and drop off independently. We briefly discuss the success of a harness-free attachment method on Common Swifts and the potential of these tags for future research. To our knowledge, our study represents the first time that such devices have been deployed on Common Swifts. Eventually, we also briefly discuss the potentialities of these devices as a tool for public engagement and raising environmental awareness, given that they can be set to transmit live-movement data to a freely accessible app oriented to the general public (Kays et al. 2015, Kays et al. 2022, Koelzsch et al. 2022).

MATERIAL AND METHODS

Colony site

The study is based on a colony of Common Swifts located in an old stable in Azzate (Varese), Italy (45.78 N, 8.80 E). The colony is hosted in a wall with several artificial cavities, built in medieval times for sparrows (*see* Ferri, 2018) and refurbished in 2021 to conserve swifts, while allowing easy access to the nests through simple doors for research purposes (Manica, 2022). Swifts of this colony normally produce only one clutch per year, but exceptional cold and rainy events of May 2023 caused a massive loss of eggs and chicks during the usual core breeding period and a significant percentage of the clutches were replaced in the following weeks. The devices' deployments occurred during the nest attendance of the replaced clutches in early June 2023. During spring 2024, a periodical count of the eggs in the nesting cavities was realized during the daylight and opportunistic checks of adults from the cavities where birds were deployed in 2023 were also realized.

Device Specifications

The devices used in this study are the 'ICARUS TinyFoxBatt' model, currently not available on the market but customed, designed and manufactured by the Wild Lab at the Max Planck Institute of Animal Behavior (Am Obstberg 1, 78315, Radolfzell, Germany). The material cost for each device is about 100 USD, and subscription costs for transmission are 12 USD/year. Supposing the potential costs of these devices in case they will reach the market in their current form, this may be around 150 USD. The average weight ± SD of the devices deployed in this study (including the fabric piece, see below) was 1.32 ± 0.04 g (N=5). This weight represented the 3.23 ± 0.19 % (mean ± SD) of the body weight of the deployed birds in our study (N=5). These devices consist of a main body and a very thin antenna, approximately six cm long (Figure 1A, see Fig. 2C in Wild et al. 2023). The devices use the 'Atlas Native' system of the digital Sigfox network for localization (https://www.sigfox.com), as detailed in Wild et al. 2023. In brief, the devices realize a trilateration geo-location based on the Sigfox antennae, thus estimating the device position (latitude, longitude, accuracy range in m) for each received message. The accuracy of the location is variable, with an average error in the order of kilometres (Wild et al. 2023). At least estimating the accuracy of locations in swifts is part of the objectives of this study, being conscious that the location error stated by Sigfox is sometimes exceeded (see Wild et al. 2023). Data collected by the device are collected by a cloud network managed by Sigfox. As a last step, users can opt to automatically transmit the data to a repository, ideally Movebank, where these are stored as any other movement data with time, geographical coordinates and any other associated data (e.g. accelerometer). All the options of Movebank are thus available to manage the data at this step, including the possibility to make them public and visible in real-time by anybody through the popular mobile app 'Animal Tracker'.

Sigfox network of antennae is currently covering the whole EU but only a few African countries (e.g. Namibia, South Africa, see https://www.sigfox.com/coverage/). This implies that the devices are unable to determine or transmit the location when the deployed individual is in areas without Sigfox coverage, such as the sea, desert, or areas with very low human impact. Noteworthily, the transmission distance of devices working through Sigfox is quite high, up to 280 km from antennae, thus notably enhancing the chance of transmissions being successful. In comparison, devices connecting at GSM antennas need to be only a few km apart to successfully connect. It should be noted that the TinyFox devices are also able to collect VeDBA (Vectorial Dynamic Body Acceleration) data (Qasem et al. 2012), a measure of animal activity, but the analysis of these is beyond the scope of the present work. The devices, in case of good network coverage, can estimate the error of each location, which is expressed in meters as a radius of a circle centred on the given location. The error estimation is trustable as validated by the producer, comparing the GPS-quality locations with the Sigfox-quality ones, collected with devices working with both systems. In this study, the devices were all set to send a location estimate every 12 hours. Without a solar panel, the device stops transmitting once the battery is depleted. The transmission efficacy in the lab was in the mean of 240 messages, thus setting two transmissions per day, the battery could potentially support a duration of 120 days (pers. comm. Timm Wild), but how long it can last once deployed on living swifts is one of the questions that this pilot test aims to answer.

Data accessibility

All the data on which this study is based are freely visible on Movebank.org under the study ‘Common swift ICARUS TinyFox 2023’, Movebank ID: 2854499986, and can be provided upon reasonable requests.

Device deployment

The devices were applied to swifts, aiming to ensure that the device dropped off from the bird after a period of a few weeks or, at the latest, during the winter body moult (see Introduction). To achieve this goal, the application followed the instructions of Raim (1978), essentially replicating the deployment method developed for passerines equipped with VHF pit-tag radio devices already in use since the '70s and '80s. The glueing of devices directly on plumage has been repeatedly used since then, even if this normally concerns devices attached to the tail (see Geen et al. 2019 for a review and O’Connell et al. 2023 for a recent application of the method), a non-viable option for swifts due to their extremely short tail.

We cut out a nylon fabric square (38 g per 100 cm²) with sides of 1.5 cm, resulting in a total weight of approximately 0.1 g. The device was then sewn onto the fabric using a Teflon fishing line. The fabric was subsequently glued to the back feathers of the swift with the following procedure. The positioning of the fabric was determined based on expert judgment, drawing on the placement of standard tracking devices, specifically just below the scapular insertion, to minimize interference with flight movements and above the uropygial gland to let it free.

Special care was taken to prevent the glue from contacting the bird's skin. To achieve this, cyanoacrylate-based superglue was carefully applied to the edges of the fabric. After allowing the glue to partially dry for a few seconds to prevent leaking, the fabric was applied to the back of the swift. The feathers to which the fabric was glued were previously ruffled with a stick to ensure that only the selected area of the plumage was involved in the adhesion. Once the glue was completely dry (30-90 seconds), the entire device was checked to confirm that it was securely attached to the feathers and not in contact with the skin.

With this method, a total of five devices were attached to adult Common Swifts with active nests on 30 June 2023 (Figures 1B and 1C). All of these individuals were attending a replacement clutch, or at least were captured in a cell with eggs, but a proportion of non-breeders are known to visit the nesting cavities anyway (see Colony site for further clarifications). The total handling time for ringing, measurements and deploying was around 10 minutes.

Movement statistics

First, we calculated for each location of each bird the NSD (Net Square Distance) from the colony with the *distHaversine* function of the *geosphere* package for R (Hijmans et al. 2022). We then tested with linear models whether the distances of the locations from the colony increased over time. We then plotted the distances from the colony for each location over time and created a map with locations and trajectories for each bird, connecting with lines the consecutive locations. Then, we used the information derived from linear models, plots and maps to qualitatively assess the type of movement of each bird. Specifically, when the distance from the colony progressively increased and the trajectory of the movements was geographically oriented, we classified these movements as migration. In the

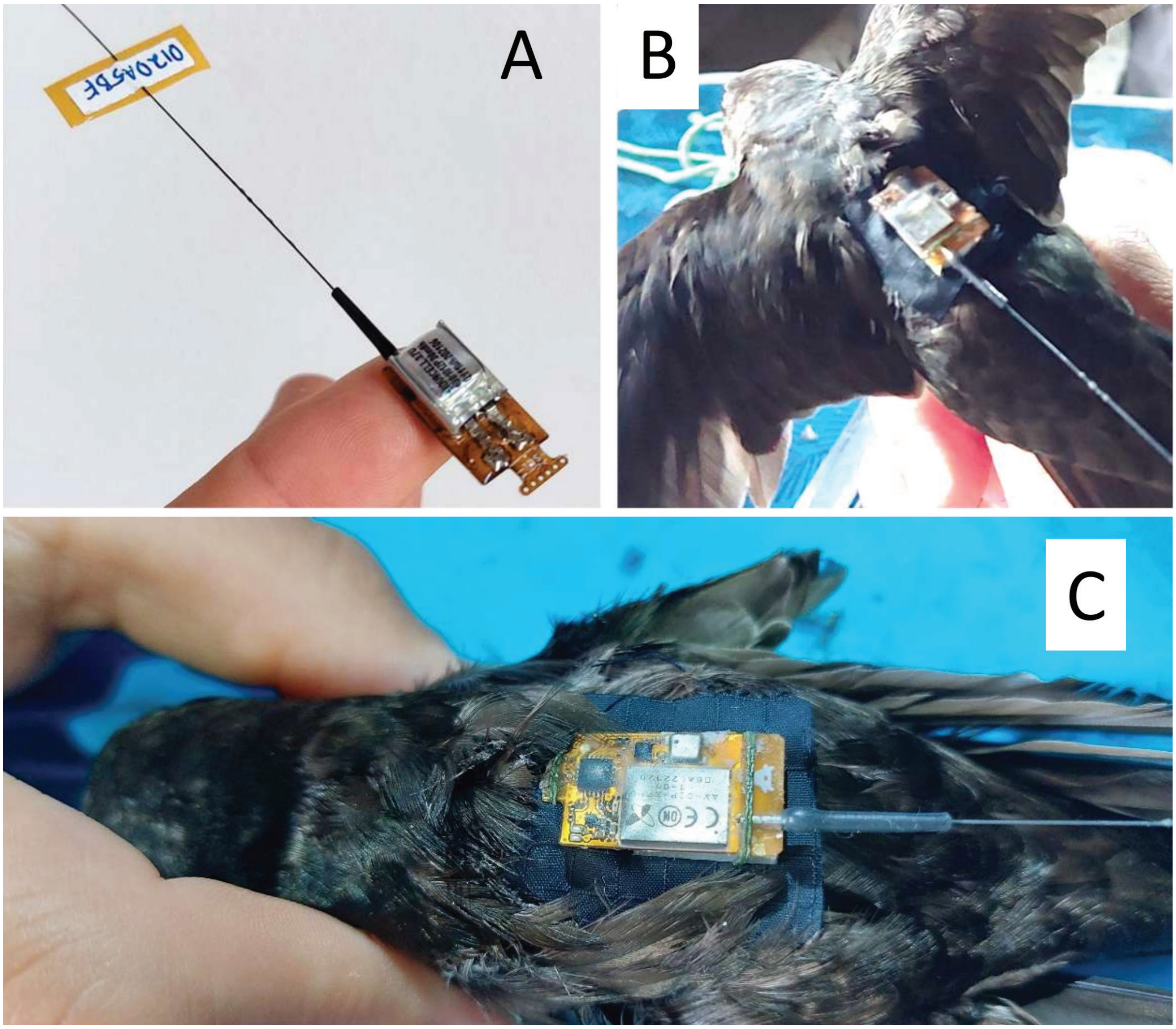

Figure 1. A. Terrestrial IoT tags, Sigfox device weighing 1.2 g, still equipped with the terminal part (bottom right in the photo), which is cut off after activation and prior to deploying. **B** and **C**: details of the device installed on a Common Swift. The device is sawn to a 1.5 x 1.5 cm fabric, which is then glued to the back feathers.

other cases, when distances were not increasing over time or movements were not spatially oriented, we classified them as local movements.

In case the distances increased over time, we calculated the distances, and the time elapsed between consecutive locations for each bird, also using the *geosphere* package (Hijmans et al. 2022). Then, we derived the speed among two consecutive locations. Eventually, for each bird, we noted the maximum and the mean speed recorded, considering all the movements among consecutive locations belonging to a given bird. We also reported the minimum total length of the recorded movements, calculated as the sum of the distances among consecutive locations. Then, aiming to extract a value comparable to those published in previous literature, we calculated the total minimum distances covered over every period of 24 h. Note that sample sizes may slightly differ among these descriptive statistics since the devices occasionally failed to collect locations at regular intervals of 12 h as they were programmed to do. Eventually, we compared through an ANOVA and post-hoc Tukey’s test whether the mean covered minimum distance and speed of the bird that migrated (i.e. B507) were significantly higher than those of the rest of the birds, expressing local movements. All the statistical analyses were run in R v. 4.2.2 (R core team 2022).

Ethical note

The swift ringing activities and device deployment have been authorized by the locally competent authority (Lombardy Region) with permits N. 6203/2023, N. 12386/2023 and 1704/2024, released after a specific positive evaluation of the deploying project by the national competent authority, ISPRA (Istituto Superiore Protezione e Ricerca Ambientale) n° prot. 0036483/2023. Precautions are taken to minimize the disturbance at the colonies.

RESULTS

Transmission success and data quality

All of the five deployed devices successfully transmitted data, for a total of 92 valid locations. Out of these, 62 were accompanied by the estimation of the location error. On average, the devices collected 19 locations each (min 6, max 45), with an overall average error of 7.44 km (max 15.6 km; min 3.4 km; sd 3.55 km). Linear models testing whether distances increased over time revealed that for three birds (A5BF, BOB9 and B255), distances from the colony were constant over the tracking period ($p>0.393$ in all the cases). On the contrary, for B507 and B682, distances increased over the tracking period significantly ($p<<0.001$ in both cases, Table 1). However, a geographical plot of the movements clearly shows how four of the birds realized non-oriented movements, also in the case of B682 (Figure 2). One individual, B507, left the colony site after deployment and undertook southwest-oriented movements, covering considerable distances each day. This behaviour well matches what is expected for a post-breeding migration and was therefore defined as 'migration'. This bird uninterruptedly transmitted data between July 1 and July 16, 2023 (Figure 3).

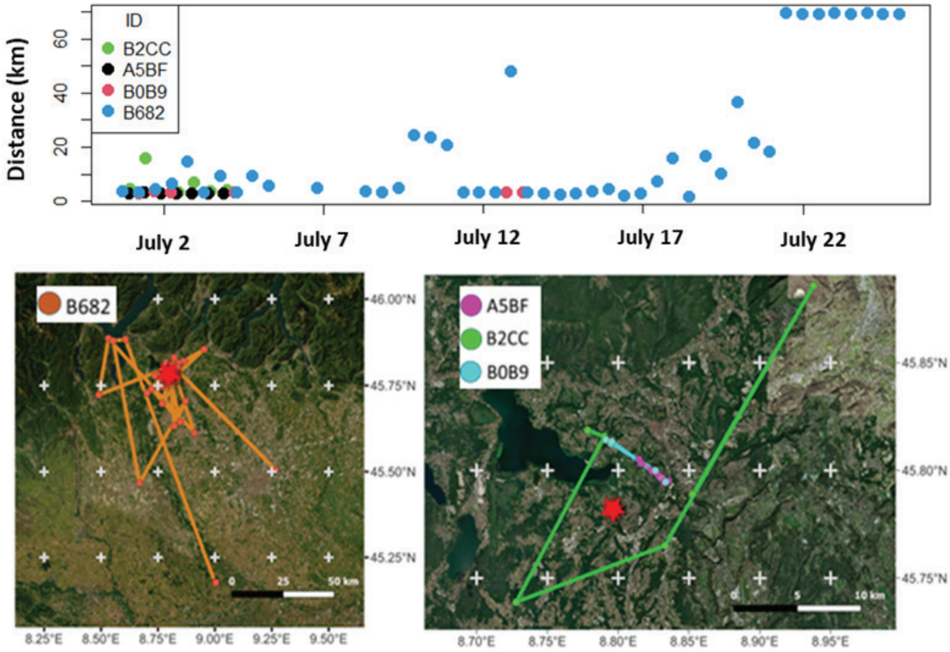

Figure 2. Local movements of four Common Swifts deployed with IoT Sigfox tracking devices at the colony of Azzate (Varese, N Italy, red star in the maps) in summer 2023. Top: plot representing the distances from the colony of each location of each bird (discerned by colour) and their change over time. Bottom left: movements track of B682. Bottom right: movement tracks of the remnant three birds.

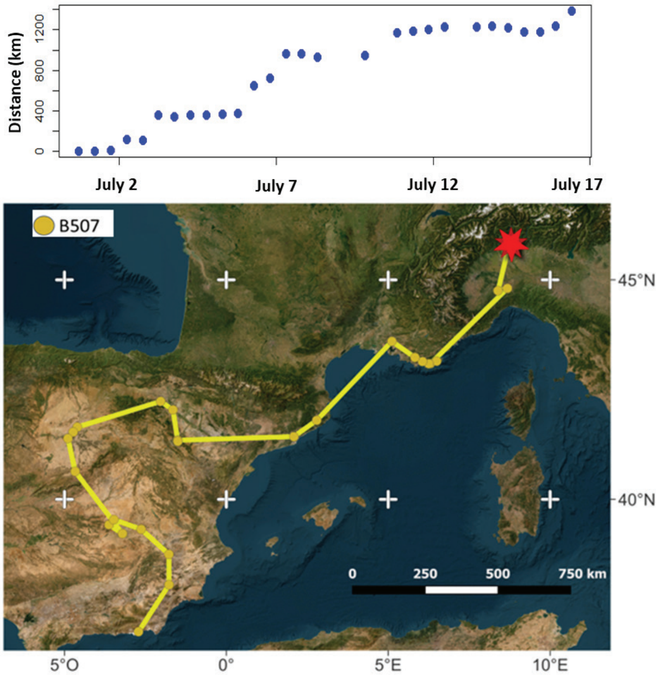

Figure 3. Migratory movements of a Common Swift B507, deployed with IoT Sigfox tracking device at the colony of Azzate (Varese, N Italy, red star in the map) in summer 2023. Top: plot representing the distances from the colony of each location and their change over time. Bottom: track of the southward migration of the bird, reaching southern Spain in 16 days.

Movement statistics

Movement statistics of each bird are presented in Table 1. We found that birds engaged in local movements resulted in moving a few kilometres, while the only bird actively migrating (B507) moved up to 482.5 km over 24 h, with a mean (± SE) of 201.3 (± 68.0) km over 24 h.

Tabella 1

DISCUSSION

In this work, we report the findings of a pilot study in which Common Swifts were deployed with IoT-enabled individual tracking devices that remotely transmit location data in real time, with no need to recapture the birds. Overall, the kind of data collected allows for novel insights into the movement ecology of swifts, even if inaccuracy in the locations and their frequency still prevent the possibility of using these for specific studies on the foraging ecology. Indeed, this possibility may be envisaged using hourly VeDBA data, which will notably improve the research potentialities of these data. The devices were deployed without a harness, and we didn't collect evidence of causing problems to the birds, suggesting this may be a common way to deploy devices on common and other swift species in the future. Indeed, an accurate return rate (or, better, true survival rate) should be assessed in the future based on multiple-year data to properly compare the return rates of birds deployed with this method and those deployed with classical harnesses. Such an approach would require a high sample size to produce robust survival estimations. To date, we can state that in 2024, one of the five deployed birds was safely back and reproduced successfully and that the device successfully fell off. Since there had been no specific effort in capturing adults at the colony during 2024, unfortunately, we can't report definitive statistics on the return rates of deployed vs non-deployed birds.

Table 1. Statistics about transmission periods and movements for the five Common Swifts deployed with IoT Sigfox tracking devices. Depending on the increase of the distance of the colony over the time (whose significance was tested through linear models) and on the spatial distribution of the locations, movements of each bird were classified either as 'local' or 'migration'. For B507, the only bird actively migrating during the tracking period, movements statistics of migration are also given.

Individual.ID	First Transmission	Last Transmission	Days of activity	Numbers of locations	Mean distance from the colony of all of the locations (km ± SE)	Distance increase over time? (yes if p<0.05)	Type of movements
A5BF	30 June	3 July	3	7	3.02 ± 0.07	p=0.428	Local
B2CC	30 June	3 July	3	6	6.51 ± 1.81	0=0.531	Local
B0B9	1 July	13 July	12	6	3.33 ± 0.08	p=0.393	Local
B682	30 June	25 July	25	45	20.4 ± 3.71	<<0.001	Local
B507	30 June	16 July	16	28	751.0 ± 86.5	<<0.001	Migration

Migration statistics for B507

Total distance travelled (km)	Max Speed (km/h)	Mean Speed ±SE (km/h)	Max distance travelled 24h (km)	Mean distance 24h ±SE (km)
2291.22	32.80	7.42 ± 1.75	482.49	201.26 ± 67.98

The deploying methodology presented in this work may be implemented in some detail, such as using surgical-conceived glues or cement (e.g. Bloch et al. 2024) instead of common super-glues.

Travel speeds in the literature concerning migrating Common Swifts peak up to 900 km/day for the subspecies *Apus apus pekinensis*, whose individuals cover the longest migration known among swifts, a distance of 13,572 ± 999 km (Zhao et al. 2022). High travel speeds have also been recorded in Common Swifts populations belonging to the nominal subspecies such as the Dutch ones that reach a migration speed of 782 km/day for an overall migration distance of ~8,800 km (Klaassen et al. 2014). Åkesson et al. (2012) found for Swedish Common Swifts, a mean migration speed of 170 km per day, with travel speeds peaking at 344 km/day. The migrating bird of our study (i.e. B507) recorded a mean migration speed of 201.26 ± 67.98 km/day, peaking at 482.94 km/day (Table 1), thus perfectly in range with the known data. Indeed, we do not have data on the migration track south of coastal Spain, as the IoT Sigfox network is not present in the sea nor in northern Africa, where the bird was heading. The spatial coverage of the Sigfox IoT network over continental Europe is therefore strongly limiting its use for tracking complete migrations of inter-continental migrants, but it is well suited for intra-Palaearctic ones.

The simple observation of mean distances of the location from the colony and the linear model testing whether these increase over the period, along with a qualitative observation based on mapping the movements, show that the quality of data collected with these new devices at least allows to discern among macro-behavioural categories (i.e. local movements vs migration). Interestingly, we did not gather any location from the nesting colony, even though at least one of the deployed individuals was re-sighted twice in its nest during the normal monitoring activities realized at the colony, thus certainly actively attending to the chicks. This may be due to both the location inaccuracies, spanning up to some km (7.44 in mean, see Results), or the difficulty in gathering signals when into the cavity or to the frequency of the location data. Indeed, the devices were set to collect a location every 12 hours, but this is certainly mismatched if compared to the frequency of the foraging trips of the breeding adults. There is some data about the foraging frequency of swifts in the literature. Through camera recording realized at a swift colony 10 km away from our study site, it was found that a single adult Common Swift fed the chicks 6-15 times per day, thus meaning up to 15 foraging trips during the daylight, lasting about 15.5 h in this period of the year at latitude 45°N (Ferrari 2021). So far, each foraging trip lasts 1-2.5 hours. Schaub et al. (2019) monitored nest visit frequency across the breeding season in a German Common Swift colony through geolocators finding a mean nest visit frequency of 5.63 visits per bird per day which is 0.32 visits per hour during daylight. In different Common Swift colonies in the district of Roth (Bavaria, Germany), Wellbrock et al. (2018) used GPS loggers saving positions every 5 min to monitor foraging flights. They found that most birds flew within 250 m and up to 7.5 km to the breeding colony (on average ± SD: 3.2 ± 1.1 km, N = 8 birds). As a further example, Carere & Alleva (1998) reported that feeding trips occurred every 3 h for adult Common Swifts attending chicks. Interestingly, they also noted that adults return to the nests up to 14 times per day without food for the chicks, but probably for other activities (Carere & Alleva, 1998).

As previously explained, our sampling rate and location error means that the total distance calculated from our movement data over a day is meaningless of the true linear distance covered in a day by adult swifts. However, for birds actively migrating over clear directions, daily distances and speed remain valid cues of the true distance and speed but must be interpreted as minimum values. Researchers who aim to study foraging behaviour should thus have in their availability devices that can collect location data at a much higher frequency and potentially with higher accuracy (e.g. Bloch et al. 2024). VeDBA data collected at 1 h frequency may be useful in future to explore the behavioural pattern of breeding birds since VeDBA values close to zero indicate the bird is static, which for swifts necessarily means being at the nest. Being a cavity-nester, the lack of locations from the colony may also be due to poor connection of the devices when the birds are sitting in the nesting cavities (rocky holes up to 30 cm depth). This may be explicitly tested in the future by leaving some devices in the cavities and checking for their ability to connect to the network.

Future research can benefit from IoT devices and harness-free deployment techniques across various fields. For instance, quantitatively assessing the distances travelled from breeding colonies can provide insights into the foraging areas utilized by breeding swifts, thus informing broader conservation efforts beyond 'simple' nest provisioning. If equipped with multiple environmental sensors and capable of collecting higher-frequency data, these devices could enhance our understanding of swift movement ecology concerning weather and meteorological conditions. Looking ahead, comparative studies of foraging and migration ecology may emerge as key research goals, such as comparing rural and urban colonies or examining the interactions between closely breeding species like Common and Pallid Swifts. Finally, we stress that swifts are among the most appreciated birds among the general public and a large number of dedicated associations or social-media groups dedicated to swifts exist in Europe. So far, studies on these species that allow the public to follow the movements of these birds in real time can act as a powerful tool for nature conservation awareness. IoT Sigfox devices perfectly fit this purpose as they were conceived and developed to send the collected data to Movebank and, from here, to make them public through the mobile app 'Animal Tracker'. As an example, we posted on X/Twitter the news about the first migrating swifts that could be followed in real-time by the general public and this post obtained over 32,000 views in a few days. We thus suggest IoT devices may also embed great potential for environmental communication and awareness-raising purposes.

In conclusion, this pilot study represents a significant advancement in using IoT technology for tracking swifts, offering valuable insights at least into their migration and minimum distances reached during foraging trips. While the findings demonstrate the potential of these devices, limitations in location accuracy and data frequency emphasize the need for further refinement. Future research should focus on enhancing device capabilities and increasing sample sizes to provide more robust data. Ultimately, this work contributes to informing effective conservation strategies for these remarkable birds.

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