Flight strategies of migrating Northern Bald Ibises: Analysis of GPS data during human-led migration flights

Christian Sperger[1], Armin Heller[1], Bernhard Voelkl[2,3], Johannes Fritz[3]

[1]Institut for Geography, Leopold-Franzens University Innsbruck. christian.sperger@gmx.net
[2]Animal Welfare Division, University of Bern, Switzerland, berhard.voelkl@vetsuisse.unibe.ch
[3]Waldrappteam, LIFE Northern Bald Ibis, Mutters, Austria, jfritz@waldrapp.eu

Abstract: *In the past, studying birds in free flight has been extremely difficult, though recently developed technologies, e.g. small and light GNSS-data loggers, allow gaining new insights into the behaviour and flight strategies of birds. As logger weight is still a limiting factor and battery size dictates the number of positional fixes, knowledge of species-specific flight strategies is still restricted. During a human led migration of fourteen juvenile northern bald ibis in 2014 we could, for the first time, record a complete GNSS dataset from all flock members over a four day migration from Salzburg to Tuscany. . Data were collected by Waldrappteam, in the course of an EU-LIFE+project. The following paper analyses this dataset. The aim of this paper is to show the different flight strategies of migratory birds and furthermore the capabilities and limitations of the used GPS-modules for the study of free-flying birds.*

Keywords: *flight strategy, northern bald ibis, GPS data*

Zusammenfassung: Das Erforschen von Vögeln und deren Flugstrategien war in der Vergangenheit schwierig. Mittlerweile ermöglichen neue Methoden und Technologien wie kleine und leichte GNSS-Datenlogger, einen tiefen Einblick in das Flugverhalten der Vögel. Trotzdem ist das Wissen über die jeweiligen Flugstrategien einiger Arten noch immer begrenzt. Weiters sind die Batterien der GNSS-Geräte aus Gewichtsgründen sehr klein was ein langfristiges Datenlogging zusätzlich erschwert. Mithilfe des „Waldrapps", gelang es nun, während der menschengeführten Migration (2014), von vierzehn Jungvögeln einen GPS-Datensatz, bestehen aus vier Flugtagen, zu sammeln. Ein Ziel dieser Arbeit ist es die unterschiedlichen Flugstrategien von Zugvögeln am Beispiel des Waldrappes aufzuzeigen und die Stärken und Schwächen der verwendeten GPS-Datenlogger für Studien frei fliegender Vögel zu prüfen.

Schüsselwörter: Flugstrategien, Waldrapp, GPS Daten

1 Introduction

The Northern Bald Ibis (NBI; *Geronticus eremita*) is a roughly 75 cm large migrating bird, with a wing span of up to 140 cm and a weight of 1000 to 1500 gram. The NBI appeared in Europe as a breeding bird until the end of the 17th century (Gesner 1557). Population decline was mainly driven by over-hunting (Unsöld & Fritz 2011). Nowadays, the NBI is one of the most endangered bird species in the world (IUCN Red List). Since 2002, the Austrian project Waldrappteam developed methods to reintroduce the NBI as a migratory species (Fritz et al. 2016). Based on this feasibility study, a European reintroduction project, co-financed by the European Union under the LIFE+ program (LIFE + 12-BIO_AT_000143) has been running since 2014. Human foster parents raise NBI chicks from zoo breeding colonies. The young birds, which are imprinted on the foster parents, are then trained to follow two ultralight aircrafts (microlights), with one of the foster parent co-pilot. In late summer a human-led migration (HLM) takes place, where the foster parents, by use of the microlights, lead the young birds from the breeding site north of the Alps to the wintering site in the southern Tuscany (Fritz et al. 2016). From 2004 to 2016, a total of 165 chicks from various Zoo breeding colonies in Austria, Germany, Switzerland and Czechoslovakia were taken for the reintroduction program and 10 human-led migrations were performed. During the first migration journeys the mean daily flight distances was about 60 km. Flights took place only in the morning to avoid thermals. Over the years, the method was optimized. The daily flights now lead over distances up to 360 km and last for up to 8 hours. A differentiated understanding of the NBI behaviour and an improved flight technique of the pilots allows leading the birds also during thermally active periods of the day, where the birds change from formation flight to soaring and gliding (Fritz et al. 2016).

A crucial aspect of the project is the successful combination of applied species conservation and basic research. The human-led migration offers the unique opportunity to equip the animals with electronic devises for collecting physiological and positional data from real migrating birds (Voelkl & Fritz in press). Accurate position data in formation flying NBIs, collected during the human-led migration, could provide the first empirical evidence that birds flying in V-formation are able to save energy (Portugal et al. 2014). Further papers, based on data collected during human-led migration flights, present the formation flight as one rare example of direct reciprocation–a form of cooperation—in animals (Voelkl et al. 2015). Another study focused on the physiology and energetics of bird migration, investigating how the metabolism changes with the length of migratory flights (Bairlein et al. 2015).

In this paper, we present outcomes of data collections with GPS devices during human-led migration flights in the course of the LIFE Northern Bald Ibis project, collected in 2014 and 2016. Our focus is on the technical description and comparison of the different flight strategies used by the birds, the active formation flight and the use of up-winds by soaring and gliding.

2 Methods

In 2014, 14 chicks of Northern Bald Ibis (NBI; *Geronticus eremita*) were taken from a free flying breeding colony at Zoo Rosegg in Carinthia, Austria. The chicks, hatched between Apr 13 and Apr 20, were raised by two experienced members of Waldrappteam, Corinna Esterer and Anne-Gabriela Schmalstieg, following a detailed protocol (Fritz 2010). On Aug 25, the human-led migration journey started from Anif in the federal state Salzburg, Austria. It led across the Alps to Carinthia and further to Italy, across the Po Valley to the mouth of the river Po (Valle Gaffaro), then further across the Apennine to Firenze in the Tuscany and finally to the WWF nature reserve Laguna di Orbetello in the southern Tuscany (Fig.1). A total distance of 944 km was covered within 11 days with 4 flight stages (min 153 km, max 301 km).

In 2016, 25 chicks hatched between Apr 1 and Apr 17 at Zoo Rosegg were raised by C Esterer and AG Schmalstieg. On Aug 19, the migration journey started from Seekirchen am Wallersee, country of Salzburg. The route was further West compared to 2014, across the Alps and the Dolomites to the Po Valle. Both routes met at the mouth of the river Po (Valle Gaffaro; Fig.1). The total distance was covered within 27 days with 8 stages (min 43 km, max 297 km; Fig.1). Main reasons for the longer duration and double the number of stages, compared to 2014, were a more demanding route with larger mountain ranges, a much larger group size and an interim lack of migration motivation in the bird group. The birds were equipped with GPS data logger only during the short track between Lugo and Faenza. The limited data set from 2016 is used for comparison reasons.

On Sep 4 2014, during the final flight leg of the migration, twelve birds lost contact to the microlights after 70 km flight, probably scared off by a helicopter from a TV team. The microlights with two remaining birds continued further south, while the lost birds, after some circles, headed back north towards the place of departure of this flight stage, located at the southern foothills of the Apennines (Fig.1). This flight occurred in absence of the foster parents and the microlights, and constitutes a unique case where the flight path of all animals of a flock, flying independently of the microlights, could be recorded.

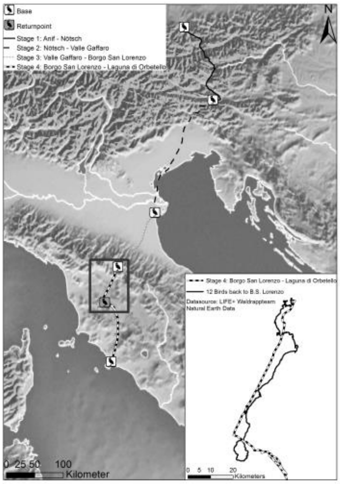

Fig. 1: Overview of human-led migration 2014 and 2016, from the country of Salzburg to the Tuscany.

At the end of July, birds were equipped with leg-loop harnesses and dummy loggers to habituate them to the procedure of being equipped with loggers and carrying an additional mass (~3.5% of the body mass of the smallest bird) during the migration. The mass of the GPS data loggers from e-obs digital telemetry (http://www.e-obs.de/) was 23 g. Given a mean body mass of 1,308 g for the birds, this was below the recommended 5% limit for flying animals (Voelkl et al. 2015). During the migration journey, before the start of a flight stage, the dummy loggers on the back of the birds were replaced by the activated data logger. In addition, data loggers were also fixed on both microlight. The logger recorded processed signals from GPS satellites and generated an NMEA data string, which was stored in binary form by the GPS data loggers. The GPS data loggers were read out by means of a base station based on radio and converted into a CSV data string (comma separated values) by means of data decoders (software). At the beginning of each stage, all the birds and both microlights were equipped with data loggers.

In a first step of data processing, flight phases were selected out of the whole data set. The data were projected into the UTM format and stored in a GRASS GIS database. Since the

GPS data loggers did not record the altitude above sea level (msl) but the altitude above the ellipsoid WGS84, these elevation data had to be corrected. For this, the Earth Gravitational Model 2008 (EGM2008) was used (Pavlis et al. 2012). In the next step, the altitude change (Δh = ht-ht-1) was calculated at the previous time for each time point. Furthermore, for each point in time, the terrain height, which is at the GPS coordinate, was determined. Table (1) gives an overview of the data recorded as well as the data derived therefrom.

As long-distance migrations are energetically demanding, it is assumed that mechanisms have evolved to cover the distance in an energy-efficient way.. One means of achieving this is by circling in ascending air masses (Voelkl et al. 2015; Voelkl & Fritz in press). In order to investigate this more closely using the collected GPS data, a script has been created using the Python programming language, which preferably captures all the circles of each data record. The script recognizes circles on the basis of three criteria: (1) the maximum duration required for a circle is 20 seconds; (2) the yaw angle difference (heading difference) of neighboring GPS coordinates summed up during a flight section is between 200 degrees and 360 degrees; (3) in addition to criterion two, the route must cross during the defined period of 20 sec. Circles were only detected using 2D criteria. The height attribute was not used.

Since the flight segments between the individual GPS positions are straight, the findings are essentially based on the calculation of the intersection point of two straight-line equations (y = k * x + d). The detected circles were stored together with the most important circle attributes in tabular and geometric form (line feature class).

In 2016, the birds were equipped with GPS Tags only (NavSpark NS-RAW: Carrier Phase Raw Measurement Output GPS Receiver).

Table 1: GPS-Datalogger Attributs

Description	**Pointattributes**
Coordinates	x und y [Dezimalgrad]
Horizontal flight speed (Groundspeed)	v [m/s]
Heading	[N: 0, 360 °]
Horizonal accuracy	Accuracy [m]
High above the ellipsoid (WGS84):	h [m]
Timestamp	t
High corrected	h (m.s.l) [m]
Delta h between two GPS-Points	Δh [m] ($\Delta h = h_t – h_{t-1}$)
Description	**Circleattributes**
Δh per Second and circle	Δh_{sec}
Max. and min. Horizontal flight speed	v_{max}, v_{min}
Heading during v_{max}, v_{min}	$heading_{vmax}$, $heading_{vmin}$

With a test setting we aimed to estimate the horizontal and vertical accuracy of the GPS tags. The results showed that the horizontal accuracy of the GPS data is at best within the range of about three meters (Fig.2b). Two devices had a remarkably deviating accuracy

(Fig.2b, No 4080, 4083), both of them were installed on the microlight. It's possible that the paraglider blocked the satellite signal,

Regarding the vertical accuracy, the main focus was on the changing height during consecutive positons ($\Delta h = h_t - h_{t-1}$). It showed, that the altitude change (Δh) remains relatively accurate as long as the accuracy calculated by the GPS loggers is constant. Fluctuations in the calculated accuracy score of the GPS logger are instantly mirrored by fluctuations in the parameter height and speed also increase. Thus, changes in these parameters can be tested quite well during constant accuracy values. In Fig.2a the amplitude of the oscillation of Δh (bottom graph) becomes smaller shortly after the fluctuation of the accuracy (top graph) decreases. Since in this study the focus is on the relative height change of the birds, slight inaccuracies regarding the absolute altitude are not essential.

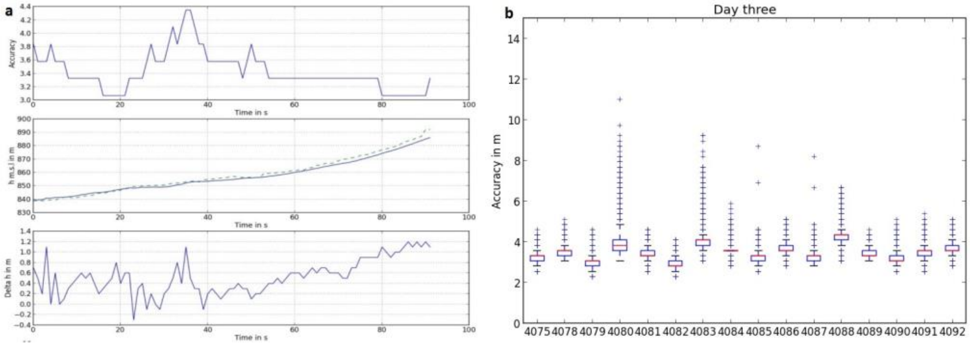

Fig. 2: Accuracy, Flight altitude und Δh (a); Accuracy from all GPS-Datalogger (b) (Boxplot: upper and lower quartile, red line: median, whiskers: 1,5 * IQR)

In the examined flight sections, it was found that for the different individuals the measured parameters resemble each other and change synchronously. For example, the birds often fly the same patterns in the soaring phase with similar vertical speed parameters (climbing values). Outliers usually occurred in the form of extreme Δh or v values and were filtered out if possible.

To link the GPS-Positions with wind data, we used the Movebank Track Annotation Tool (Dodge et al. 2013) with data (ERA Daily Interim) from the European Centre for Medium-Range Weather Forecasts (http://www.ecmwf.int/).

3 Results

3.1 Characterization of the flight strategies

We compared two characteristic flight strategies, which can be observed regularly during the migration flights of the NBI, the active formation flight and the use of up-winds by soaring and gliding (Voelkl & Fritz in press). For the analysis, characteristic sequences for both flight strategies where chosen, both in the Po Valley with flat underlying terrain, almost at sea level. The soaring-gliding sequence is in the afternoon of the second flight stage, Aug 28 2014 14:45 to 15:30 CET (Fig.3). The active flight sequence is in the morning of the third flight stage, Aug 30 2014 9:00 to 9:30 CET (Fig.3).

During the soaring-gliding sequence in the early afternoon, the birds regularly used thermal up-winds. During the 45-min sequence, they performed six soaring phases. These soaring phases are characterised by a positive vertical speed (height increase; Fig.3a) and a low and oscillating horizontal speed (ground speed Fig.3b). Soaring phases are made up of individual circles (Fig.2c), with a mean of 11 seconds per circle. The mean vertical speed (height increase) during soaring was 1,7 m/s (min 0,75 m/s, max 1,94 m/s). The mean absolute height increase per soaring phase was 60 m (min 22 m, max 106 m). Soaring phases lasted for a mean of 57 seconds (min 17 s, max 96 s).

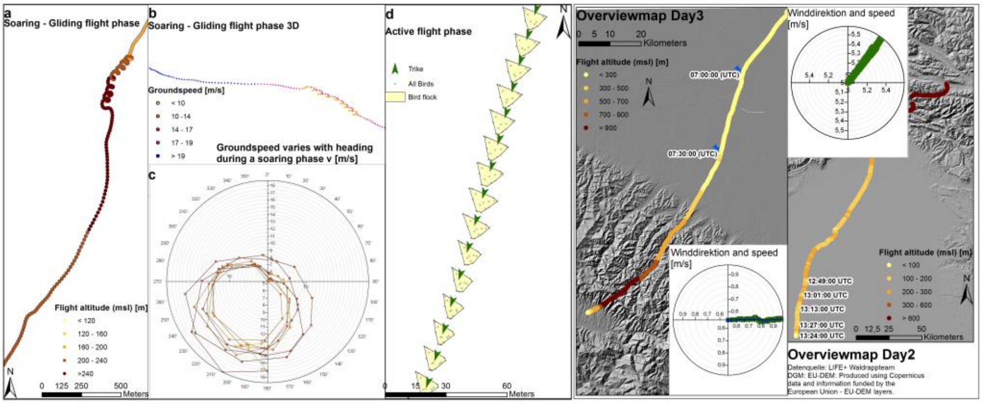

Fig. 3: Soaring-gliding phase (a, f); Soaring-gliding phase 3D (b); Groundspeed varies with heading during soaring (c); Active flight phase (d, e)

The soaring phase is followed by a gliding phase, which, in the narrow sense, is characterized by a comparatively high horizontal speed (ground speed) and a negative vertical speed (height decrease). In the regarding sequence the mean horizontal speed (ground speed) was 17 m/s (max 26 m/s) and the mean vertical speed was -1,3 m/s (max -3,8 m/s). During such gliding phases the birds usually form a V-formation and don't flap. This gliding phase turns into a phase with active flight, as described in the following paragraph. It lasts till the birds find another air column to start again with the soring phase. Thus, the soaring-gliding flight contains of three distinguishable, recurring phases, soaring, gliding and active flight (Fig.4).

During a characteristic active flight phase, the birds continuously head towards the destination, in our case SSW (Fig.3d). In the regarding sequence, the mean horizontal speed (ground speed) was 14,7 m/s (min/max). The birds showed very low fluctuation of the vertical speed, as characteristic for the soaring-gliding flight, apart from a slight continuous increase of the flight level during the 30-min sequence (60 m, from 220 m to 280 m msl). Due to previous studies with Northern Bald Ibises the birds fly in a typically V-shaped formation (Portugal et al. 2014; Voelkl et al. 2015). The mean wing beat frequency during active flight is 3-4 beats/sec, with intermediate short gliding phases. (Fritz et al. 2008).

3.2 Comparison of the flight strategies

During the active flight, the flight route (26.4 km) almost equals the straight air-line distance towards the destination (26.2 km; Tab.2). During the soaring-gliding flight, in contrast, the flight route (43.1 km) is 8 % longer than the air-line distance (39.9 km). This difference is presumably partly due to the birds' need to search for thermal updrafts along the route and to a lesser extend due to the circling itself.

During the soaring-gliding flight the horizontal flight speed varies within a broad range (from 4 m/s to 26 m/s; Tab.2, Fig.4) and in a periodic way, in accordance with the three phases described above (Fig.4), while during active flight the speed range is much lower (12 m/s to 17 m/s). Also, the vertical flight speed varies during soaring-gliding, with positive values during soaring (mean +1.7 m/s) and negative values during gliding (mean -1,3 m/s; Tab.2, Fig.4), while during the active flight the vertical speed is usually close to zero. According to the differences in the vertical flight speed, also the flight altitude range varies, with 224 m during the soaring-gliding sequence and 60 m during the active flight sequence.

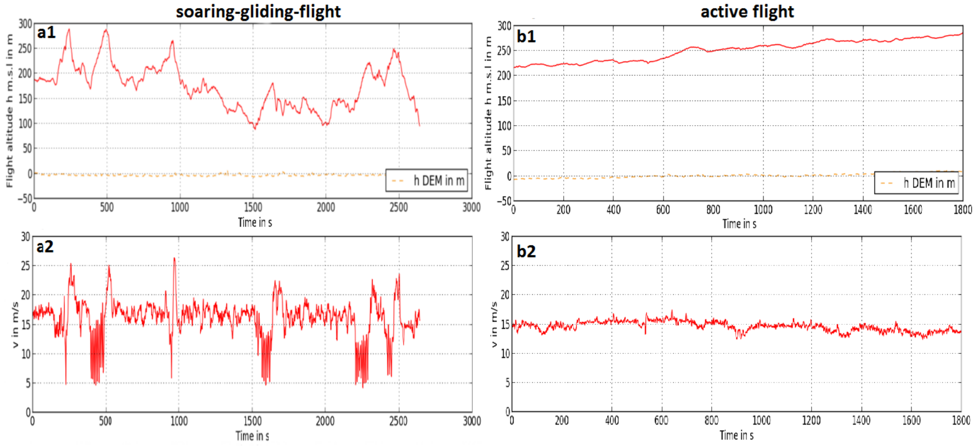

Fig. 4: Soaring-Gliding flight (a) versus active flight (b); high profile (a1, b1); Groundspeed (a2, b2)

The mean horizontal speed along the air-line distance from the starting point to the endpoint of each sequence is quite similar, with 14.67 m/s for the active flight and 14.55 m/s for the soaring-gliding flight. However, it must be taken into account that the wind strength and wind direction differed during the two flight sequences (Fig. 3e,f). During the active flight sequence, the wind speed was low (mean wind 0,7 m/s E) and from the side. In contrast, during the soaring-gliding sequence there was substantial wind (mean 4.5 m/s NE). During gliding flight and active flight the wind was supportive (tailwind) and during the soaring phase is caused a significant drift of the birds in the flight direction (Fig.3c). When subtracting the estimated supportive wind component, the horizontal speed along the air-line distance during the active flight sequence (14.32 m/s) was about 42 % faster compared to the soaring-gliding sequence (10.05 m/s)

Table 1: Comparison of the two flight strategies.

Flight strategy	**Active flight**	**Soaring-gliding flight**
Flight route / air-line distance	26.4 km / 26.2 km	43.1 km / 39.9 km
Horizontal flight speed (min / max)	12 m/s /17 m/s	4 m/s / 26 m/s
Vertical flight speed (min / max)		-3,8 m/s / 1,94 m/s
Flight altitude range	60 m	224 m
Wind strength and direction (estimated supportive component)	0.7 m/s ENE (0.35 m/s)	4.5 m/s NE (4.5 m/s)
Mean horizontal speed along the air-line distance (corrected value)	14.67 m/s (14.32 m/s)	14.55 m/s (10.05 m/s)

4 Discussion

After the analysis of the dataset it can be said that different flight strategies can be clearly revealed by the sampled data. The soaring flights, for instance, can be distinguished from the active and gliding flights by higher positive Δh as well as lower and oscillating horizontal flight speed. This fact was also detected in the course of a research on golden eagle taken by Katzner et al. (2016).

The horizontal flight speed (ground speed) is a combination of the effects of different wind components with the actual flight speed. According to the dataset the birds achieved a horizontal flight speed of 14,32 m/s during the active flight. In earlier studies (Fritz et al. 2008) the horizontal flight speed was indicated 12,5 m/s. Itis difficult to estimate to what extent wind speed and direction influences the horizontal flight speed of the active flight. Also, the lack of experience of the birds to fly in V-formation at the beginning of the migration can be a reason for the lower flight speed in 2008. The drift of the soaring phases is a clear indication of winds (Fig.5f; Fig.3a). Accurate wind data is often difficult to obtain. Also, the wind component varies with alternating flight level, which is of particular relevance during soaring. This can be seen in the changing wind drift during soaring, the oscillating speed depending on the heading and the amplitude of this oscillation (Fig.5f, a, d). The use of weather models, as done by Safi et al. (2013), may provide clues about horizontal and vertical winds.

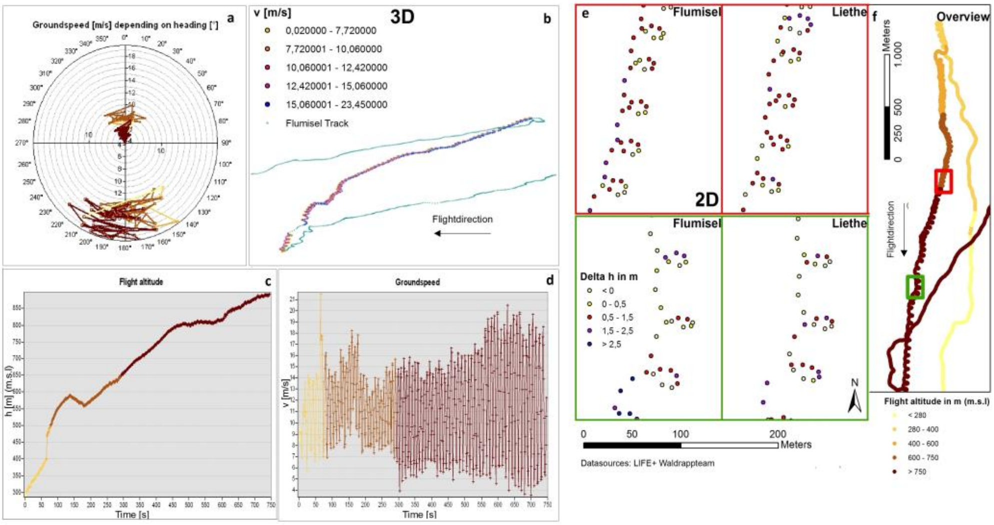

Fig. 5: Example from a soaring phase (Day 4). v_{max}, v_{min} differs with Heading (a) and Flight altitude (d); Overview (f 2D, b 3D); Short circlesequences (e); Flight altitude (c)

Including data of a weather model from the European Centre for Medium-Range Weather Forecasts (http://www.ecmwf.int/) allows explaining the unexpected small difference of the mean flight speed during the soaring-gliding phase at the second flight day and the active flight phase at the third day. However the wind data have a spatial resolution of 0.75° and a temporal resolution of 6 hours (movebank.org track annotation service), leading to according uncertainties concerning wind speed and directions. Moreover, in a small mountainous environment like the Apennines local winds on a small scale can differ substatially from modelled wind.

The parameters like the climbing and gliding rate vary strongly due to the atmospheric conditions. This can be seen during the fourth stage, when the birds flew alone and higher climbing rates were achieved (above Florence at 12:20 ECT mean 2,4 m/s max 3 m/s min 1,5 m/s), furthermore the flight altitude above ground was apparently higher than in the former stages (up to 800 m near Florence). The difficult wind condition on that day makes it hard to interpret the fourth flight day so the data can only be used for comparison. Also, the fact that the flight back to Borgo San Lorenzo took six times longer than the flight to the refuelling stop let assume that this flight was energetic inefficient. Typical flight strategies can therefore not be explained with this part of the dataset.

Initial tests of the GPS loggers suggested accuracies for absolute spatial positions in the horizontal plane of ±3 m. These findings are in accordance with the often proclaimed accuracy of uncorrected GPS data of ±2.5 m. With such an accuracy it seems questionable whether estimates about fine-scale positional changes, as required for studying bird formation flight, can be made. However, as ourdiscussion of time-changing parameters has shown, the GPS loggers provided data of sufficient accuracy and precision over substantial proportions of the flight. For example, in some examined flight sections it could be determined that the recorded parameters, like the change in altitude, change in the speed with the direction of flight and the altitude, are very similar for all examined birds. When the birds were flying in the circular series (compare Fig. 5 e), they had closely matching climb rates at corresponding positions. In the case of strongly fluctuating accuracies, outliers usually appear in the form of extreme Δh or v values. Such outliers (compare FIG. 5d between 50 and 100 seconds) were filtered, if possible.

Summarizing we can say that the use of lightweight GNSS technology allows a series of new insights into flight behaviour and flight patterns of migrating birds. Bird migration has attracted a lot of attention from scientists for several reasons. For one, it is an important aspect in the life history of many bird species. About 1800 bird species (almost 20 percent of all bird species) are long-distant migrants. Evolutionary biologists have speculated about the benefits and evolutionary origin of migration habits, but recently climate change has added a new level of topicality to bird migration, as changing living conditions are likely to change migratory patterns with potential effects on bird populations and animal conservation efforts. At the beginning of the twentieth century scientists and interested lay people started the bird ringing scheme, where captured birds were fitted with small metal rings with a unique identification number. Re-capturing ringed birds at other locations allowed the re-construction of migration routes and the identification of wintering areas. Since the invention of the ringing scheme, over 100 million birds have been ringed, providing valuable information and making it by far the largest citizen science project to date. Though, with the development of lightweight data loggers a new era of bird-migration research has begun. So far, most research projects applying GNSS technology have focused on long-term data collection over periods of weeks to several months or years. The purpose of those studies was to gain new insights into large-scale movement patterns, though these long data logging periods come at the expense of temporal resolution (with positional fixes at hourly or daily rates, only). Here, we have investigated and demonstrated the potential for using GNSS technology for studying fine-scale movement behaviour of birds by recording positional data at a temporal resolutions of 1 second or even higher. Taking such an approach allows us to investigate details of flight manoeuvres and flight strategies of free flying, migrating birds.

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