

RESEARCH ARTICLE

Geolocation with a magnetic sensor

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Abstract

1. Many migratory animals use spatial variation in the Earth's magnetic field for orientation and navigation. This raises the possibility of exploiting these same cues to geolocate and track migratory animals throughout their annual journeys. Magnetic-based geolocation could be particularly valuable for small aerial and aquatic species, for which the most precise pressure-based geolocation cannot be applied.
2. We developed a novel geolocation method, implemented in the R package GeoMagR (<https://geopressure.org/GeoMagR/>) that uses three-axis magnetic field measurements from lightweight multi-sensor tags. The workflow consists of: (i) tilt compensation and magnetic calibration; (ii) extraction of time series of magnetic intensity and inclination; and (iii) generation of spatial likelihood maps using the World Magnetic Model (WMM). We evaluated the method using field data to assess achievable spatial precision and potential complementarity with other geolocation techniques.
3. Magnetic geolocation achieved a typical spatial accuracy of ~150km in latitude but provided little constraint in longitude. When combined with light-based geolocation, which offers high longitudinal accuracy but poor latitudinal resolution, the integration markedly improved overall position estimates.
4. Magnetic geolocation is a viable complementary tool for tracking small avian species, particularly in contexts where pressure-based methods cannot be used. By independently resolving latitude, it enhances spatial inference when integrated with other geolocation data sources. This processing of 3D magnetic and acceleration data from geolocators also extends their use beyond positioning, enabling applications in studies of behaviour and navigation.

KEYWORDS

biologging, bird migration, geomagnetic models, GeoPressureR, likelihood mapping, magnetometer

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1 | INTRODUCTION

Tracking the movements of small-bodied animals remains difficult because biologging technologies are limited by size, weight and power constraints (e.g. Bridge et al., 2011). For collecting full tracks of small-sized avian species, archival sensors, devices that store data for post-retrieval analysis, are often the only available option. Three main approaches are currently used for archival geolocation: light-level geolocators, GPS loggers and pressure sensors. Each offers distinct trade-offs in spatial accuracy, temporal resolution and cost.

The effectiveness of these methods is highly context dependent. The widely used light-level geolocation performs poorly in low or variable light environments, such as dense forests and offers limited latitudinal resolution, particularly near the equinoxes (Fudickar et al., 2012; Lisovski et al., 2012, 2018). Moreover, it typically yields just two positional estimates per day and requires long time series to mitigate noise in sunrise/sunset detection. Archival GPS loggers provide much greater spatial precision, but their high energy demand often limits the number of positions that can be recorded (Tomkiewicz et al., 2010). Like light-level sensors, GPS loggers can also struggle in forested habitats (McKinnon & Love, 2018). More recently, pressure-based methods have enabled geolocation at high spatial and temporal resolution and have been successfully applied to forest-dwelling and nocturnal species (Nussbaumer, Gravey, Briedis, & Liechti, 2023). However, this method requires that the bird's altitude remains approximately constant over time intervals and is poorly suited to species that spend most of their time in flight, such as aerial insectivores like swifts. No single method is universally optimal; rather, geolocation approaches must be carefully matched to species ecology and study goals. Increasingly, researchers are employing multi-sensor geolocators that combine pressure, light and acceleration data to improve trajectory estimation.

Lightweight multi-sensor geolocators can include a three-axis magnetometer that records the three components of the Earth's magnetic field (Liechti et al., 2018). While such magnetometers have been used in studies of body orientation and flight behaviour of larger birds (Connors et al., 2021; Schoombie et al., 2023; Williams et al., 2015, 2017, 2020), their potential for direct geolocation remains largely untapped (but see Bidder et al., 2015; Gunner et al., 2021). The Earth's magnetic field varies systematically across the globe in intensity (field strength), inclination (angle between the field and the horizontal plane) and declination (angle between magnetic north and geographic north). These known spatial variations allow sensor measurements to be matched to geomagnetic models, enabling the estimation of geographic position (Laundal & Richmond, 2017).

Here, we present a new method to reconstruct geographic location based on magnetic field measurements. We evaluate its performance in field conditions and assess its potential as a complementary geolocation tool.

2 | METHODS

We present a three-step method for magnetic geolocation (Figure 1): (1) data processing, (2) extraction of time series for magnetic intensity and inclination and (3) construction of likelihood maps.

This workflow is implemented in the R package GeoMagR (<https://geopressure.org/GeoMagR/>) (Nussbaumer, 2025) which provides two core functions: `geomag_calib()` (encompassing steps 1 and 2) and `geomag_map()` (step 3). These functions are designed to integrate seamlessly with the GeoPressureR package (Nussbaumer & Gravey, 2022) for comprehensive geolocation analysis. GeoMag uses magnetic field data retrieved from the World Magnetic Model (NOAA NCEI Geomagnetic Modeling Team & British Geological Survey, 2024a) using the `wmm` package (Frierson, 2020).

2.1 | Data processing

In this section, we compute the magnetic intensity F and inclination I from the raw measurements of three-axis magnetic sensors m_x, m_y, m_z . Retrieving these variables requires correcting the raw magnetic data for (1) hard and soft iron effects through calibration and (2) change in coordinate frame with a tilt compensation. Building on established methods (`Gundog.Compass()` in Gunner et al., 2021; STMicronics, 2010; Vitali, 2016), we process the data with a slightly modified procedure, as outlined below.

2.1.1 | Magnetometer calibration

Calibration of magnetic sensors is essential to obtain accurate measurements of the Earth's magnetic field (e.g. Gebre-Egziabher et al., 2006; Lenz & Edelstein, 2006). Raw measurements are typically affected by (1) hard iron biases, which introduce a constant offset and (2) soft iron effects, which induce orientation-dependent distortions due to magnetised materials near the sensor.

Under ideal conditions, calibration is performed in the laboratory by rotating the sensor through all orientations while recording the magnetic field at high temporal resolution. In absence of distortion, measurements form a sphere centred at the origin. However, in practice, they describe an offset ellipsoid (see example in Appendix A). Fitting this ellipsoid yields correction parameters, with its centre representing the hard iron offset and its shape capturing soft iron effects. These parameters are then used to construct a transformation that corrects the raw magnetic data and enables accurate field measurements.

In the context of lightweight archival geolocators, applying such laboratory calibration is often impractical. Device configuration can change between calibration and deployment, for example due to battery replacement or change of firmware to adjust temporal resolution, which alters local magnetic conditions. As a result, laboratory-derived parameters may not accurately reflect field conditions.

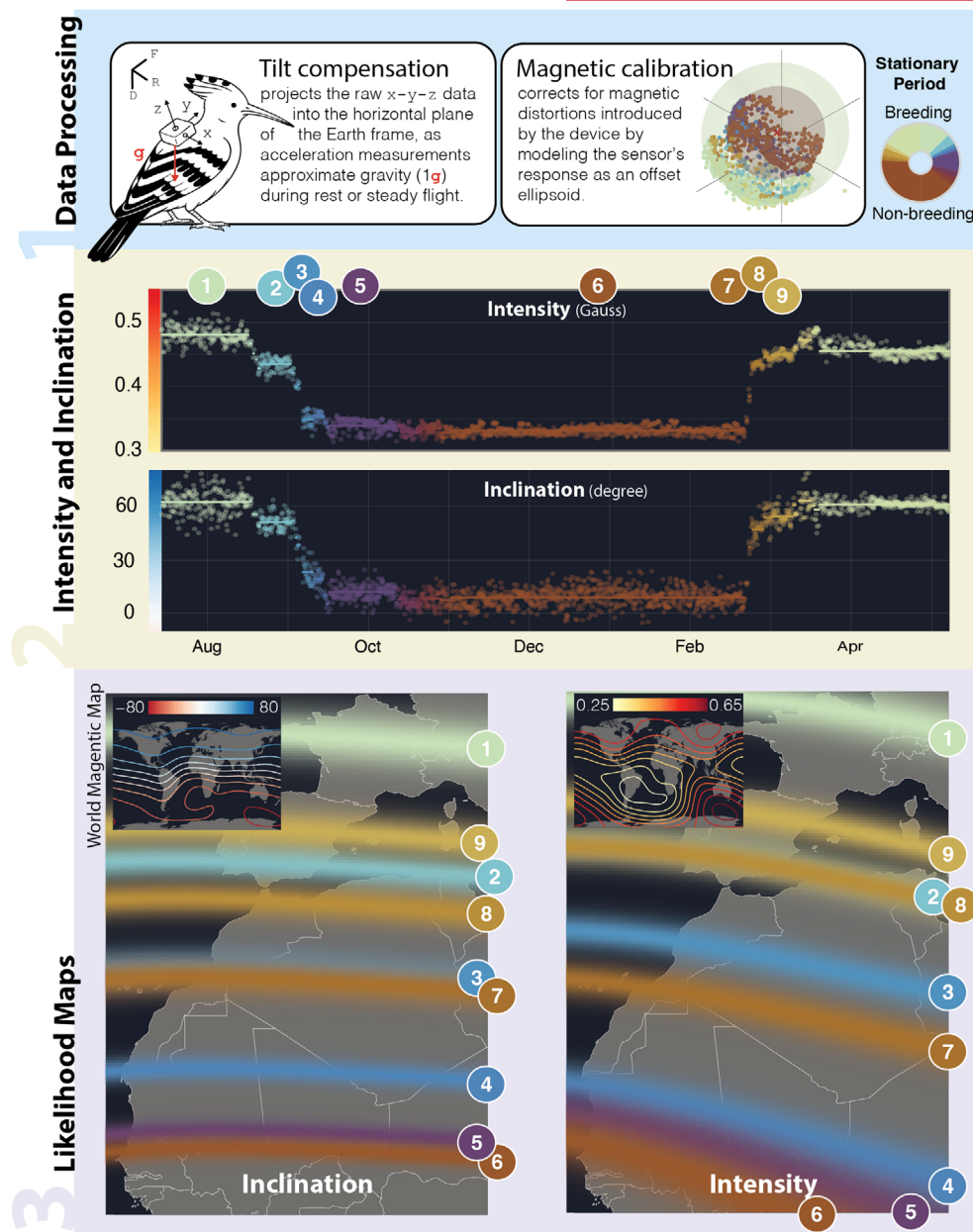


FIGURE 1 Schematic overview of the methodology for geolocating migratory birds using time series of three-axis magnetometer data. (Top) Raw sensor readings are first corrected for orientation (i.e. tilt compensation, left) using concurrent accelerometer data to project measurements into the horizontal plane of the Earth frame. Magnetic field-data calibration (right) then adjusts for persistent distortions in the Earth's magnetic field by fitting an ellipse, accounting for hard, soft iron effects and adjustment of intensity for each location (indicated by colour gradient). (Middle) For each data point, magnetic inclination (angle between the horizon and the magnetic field vector) and intensity (field strength) are computed from the corrected data. These features show consistency within stationary periods (colour gradient and numbering) and variation between periods, reflecting movement across different geographic regions. (Bottom) Observed inclination and intensity are compared to global magnetic reference maps (World Magnetic Model; top-left insets in maps). For each stationary period (colour gradient and number), a likelihood map of possible locations (colour intensity) is computed using a hierarchical Gaussian error model that incorporates both measurement noise and stationary period-specific noise.

We therefore adopt a calibration approach based exclusively on data collected during deployment, typically spanning 1 year. This approach avoids the need for dedicated calibration procedures and allows consistent treatment of all datasets, including those lacking laboratory calibration. Because birds move across regions with different

magnetic field intensities, the observed data correspond to ellipses of varying radii. To account for this, we include a scaling parameter for each unique location of the birds (i.e. stationary period), allowing separation of sensor-specific distortions from spatial variation in field intensity. The full procedure is described in [Appendix A](#).

2.1.2 | Tilt compensation

Because magnetic sensors capture the magnetic field along the device's three axes (x, y, z), any tilt, due to pitch or roll of the bird and device, misaligns these axes with the Earth's horizontal plane. To account for this, tilt compensation uses three-axis acceleration data, which reflect the direction of gravity, to determine the sensor's pitch and roll angles. This approach is only reliable when the device is in a quasi-static state, that is, when acceleration is dominated by gravity. By incorporating these angles, the magnetic field measurements can be projected onto the horizontal plane of the Earth frame for further analysis.

Inclination was therefore computed only from quasi-static samples. These were identified by retaining measurements where the acceleration norm was close to 1g (± 0.15 g), followed by removing outliers using a median absolute deviation (MAD) filter.

Pitch (tilt forward or backward) and roll (tilt to the left or right) were then computed from the accelerometer data. We use a forward-right-down device coordinate system, where the x-axis points forward, the y-axis to the right and the z-axis downward. Under static conditions, the accelerometer measures gravity as a positive acceleration along the z-axis (i.e. +g aligned with the downward axis). Pitch (ρ) is defined as positive for nose-up rotations (rotation around the y-axis), and roll (γ) as positive for right-wing-down rotations (rotation around the x-axis). These angles are computed as:

$$\rho = \arcsin\left(\frac{-a_z}{\|a\|}\right)$$

and

$$\gamma = \text{atan2}\left(\frac{a_y}{\|a\|}, \frac{a_x}{\|a\|}\right),$$

where a_x , a_y and a_z are the accelerometer readings along the x, y and z axes, respectively.

The raw magnetic measurements (m_x, m_y, m_z) are then projected onto the horizontal plane of the Earth frame using the rotation matrix operation,

$$\begin{bmatrix} m_{x'} \\ m_{y'} \\ m_{z'} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \rho & \sin \rho \\ 0 & -\sin \rho & \cos \rho \end{bmatrix} \begin{bmatrix} \cos \gamma & 0 & -\sin \gamma \\ 0 & 1 & 0 \\ \sin \gamma & 0 & \cos \gamma \end{bmatrix} \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix}.$$

2.2 | Intensity and inclination

The magnetic field intensity can be computed from either the norm of the calibrated or the projected magnetic vector as it is invariant to rotation,

$$F = \sqrt{m_{x'}^2 + m_{y'}^2 + m_{z'}^2} = \sqrt{m_x^2 + m_y^2 + m_z^2}.$$

Inclination is computed for quasi-static samples using the tilt-compensated magnetic vector,

$$I = -\arcsin \frac{m_{z'}}{F}.$$

To enable further use of magnetometer data (see Section 4.2.1), we additionally specify the derivation of heading.

The magnetic heading H_m is computed using the magnetic north as reference with

$$H_m = \text{atan2}\left(-m_{y'}, m_{x'}\right).$$

Once we know the approximate position of the bird, we can retrieve the declination angle D at this location and can thereby correct for the true geographical heading H_g of the bird with

$$H_g = H_m - D.$$

This correction is usually quite small in most of Africa and Europe (2.5–6°).

2.3 | Likelihood maps

Having derived magnetic intensity (F) and inclination (I) from calibrated and tilt-compensated magnetometer data, we estimate geographic location by matching these values to the World Magnetic Model (WMM) (NOAA NCEI Geomagnetic Modeling Team & British Geological Survey, 2024a). The WMM describes how the Earth's magnetic field varies in space, providing global maps of intensity and inclination. These fields are generally smooth at large scales, offering a structured reference for position estimation.

Similar to previous approaches (Basson et al., 2016; Nussbaumer, Gravey, Briedis, Liechti, & Sheldon, 2023), we segment the trajectory of a bird in both time and space. Temporally, the trajectory is represented as alternating stationary periods and continuous flights, with birds assumed to remain at the same location for durations ranging from less than an hour to several months. Spatially, we define stationary positions on a predefined grid, typically 0.1°–0.25° (~10–30km).

For each stationary period, we aim to produce a spatial likelihood map for intensity F and inclination I separately. To simplify notation, we denote either variable as $x \in \{F, I\}$. The likelihood L_x is modelled as a Gaussian distribution, expressing the probability of observing the measured magnetic values given that the bird was at a specific location. Prior to likelihood computation, magnetic time series were filtered within each stationary period to remove outliers using a median absolute deviation (MAD) criterion. This filtering was applied separately to intensity and inclination. To estimate L_x , we compared the time series of observed magnetic measurements x^{obs} to the WMM modelled values x^{WMM} at each grid cell of the predefined spatial grid. We consider that the difference between observed and modelled values arises from two sources of variability: (1) a measurement error σ_e which represents sensor-level variability that affects each observation and (2) a stationary-period-specific bias σ_m capturing systematic deviations that are constant within each period but vary across periods. By

treating the stationary-period bias as a random effect and integrating it out analytically, we obtain the following marginal Gaussian likelihood

$$L_x(d|\sigma_e, \sigma_m) \propto \exp\left(-\frac{1}{2\sigma_e^2} \sum_{i=1}^n \epsilon_i^2 + \frac{1}{2} \frac{\sigma_m^2}{\sigma_e^2(\sigma_e^2 + n\sigma_m^2)} \left(\sum_{i=1}^n \epsilon_i\right)^2\right) \quad (1)$$

where $\epsilon_i = x_i^{\text{obs}} - x_i^{\text{WMM}}$ and n is the number of observations. This formulation corresponds to a Gaussian likelihood with a random effect (a hierarchical or mixed-effect Gaussian model), where the stationary-period bias is treated as a latent variable integrated out analytically (Laird & Ware, 1982; Pinheiro & Bates, 2000). We demonstrate in Appendix B how the variance σ_e and σ_m are empirically estimated.

Evaluating this expression across all map locations yields a spatial likelihood map, which can then be used to infer the most probable location of the bird during stationary periods. Importantly, these likelihood maps can be combined with other likelihood maps (e.g. derived from pressure or light) into a movement model, where a probabilistic transition model between stationary periods is assumed, resulting in a more accurate trajectory (e.g. State-Space Models). Such a model is already implemented in the GeoPressureR R package (Nussbaumer, Gravey, Briedis, Liechti, & Sheldon, 2023), allowing magnetic likelihood maps generated with GeoMagR to be directly incorporated into the movement model.

2.4 | Accuracy assessment of magnetic and light geolocation

We assessed the spatial accuracy of magnetic likelihood maps using data from five studies: 22 Great Reed Warblers (*Acrocephalus arundinaceus*, Emmenegger et al., 2021), 21 Eurasian Hoopoes (*Upupa epops*, Arlettaz et al., 2010; Bächler et al., 2010; Liechti et al., 2018; Schaub et al., 2025), 5 Woodland Kingfishers (*Halcyon senegalensis*, Nussbaumer et al., 2025; Rime, Osinubi, et al., 2025), 4 Ring Ouzels (*Turdus torquatus*, Barras et al., 2021, 2025) and 3 Eurasian Nightjars (*Caprimulgus europaeus*, Lathouwers et al., 2022, 2025). All birds were equipped with GDL3-PAM multi-sensor loggers from the Swiss Ornithological Institute measuring light (interval: 2–5 min), pressure (5–30 min), activity (5 min; a proxy of body movement derived from acceleration), three-axis magnetic data and acceleration (3–6 h). All these datasets were already processed with the standard GeoPressureR analysis pipeline (Nussbaumer & Nussbaumer, 2024) including the manual labelling of pressure and activity data enabling the identification of stationary periods.

To enable performance assessment, we first derived a reference trajectory for each track using the most accurate geolocation method currently available in the absence of GPS: pressure-based locations with a typical precision of <50 km (Nussbaumer, Gravey, Briedis, & Liechti, 2023) combined with a Hidden Markov movement model that integrates flight duration and wind data (Nussbaumer, Gravey, Briedis, Liechti, & Sheldon, 2023). To ensure an independent

evaluation of light-based geolocation, we repeated the original GeoPressureR analysis while excluding light data, but otherwise retaining the same model parameters. The most likely trajectory from this new movement model was therefore used as a model-based reference for comparison, and distances to this reference should not be interpreted as distances to the true trajectory.

We then processed the magnetic data from these tags following Sections 2.1 and 2.2 and built the magnetic likelihood maps of inclination and intensity for each stationary period as detailed in Section 2.3. From each magnetic map, we extracted the isoline of highest likelihood and computed the shortest Euclidean distance from the isoline to the reference GeoPressureR position.

We then applied the same approach to light-level geolocation using the pre-computed light likelihood maps included in the datasets and generated with GeoPressureR. For each stationary period, we identified the position of maximum likelihood and measured the distance from the reference. Given the uneven precision of light-level geolocation (greater in longitude than in latitude), we computed latitudinal and longitudinal distances separately.

Together, this workflow yielded four distance measures per stationary period, all relative to the reference GeoPressureR position: (i) inclination-based isoline distance, (ii) intensity-based isoline distance, (iii) light-only latitude distance and (iv) light-only longitude distance.

2.5 | Application to aerial species

Magnetic-based geolocation is particularly valuable for aerial foraging or non-stop flying species, where pressure-based methods are unreliable due to continuous vertical movement. To evaluate the performance of the magnetic geolocation approach in such cases, we selected a representative migration track from each category: an aerial-feeding species, the Eurasian Bee-eater (*Merops apiaster*) tagged in Germany and a non-stop flying species, the Alpine Swift (*Tachymarptis melba*), tagged in Bulgaria. Both individuals carried multi-sensor geolocators as part of previous tracking studies (Hahn et al., 2020; Meier et al., 2020).

Stationary periods for aerial species cannot be as reliably identified using acceleration and pressure data as in flapping birds. For the present study, however, we employed an alternative approach: breeding and non-breeding stationary periods were manually identified using a combination of twilight variability, sustained pressure drops and high activity from acceleration data. The migratory phase, defined as the interval between the end of the breeding period and the start of the non-breeding stationary period, was segmented into one stationary period per day. Daily aggregation was chosen as a pragmatic compromise, as it typically ensured enough quasi-static samples while keeping the number of discrete movement states limited.

For each stationary period, four likelihood maps were computed: one based on light level, one on magnetic inclination, one on magnetic intensity and a joint likelihood obtained as the product of these three. Trajectories were reconstructed by selecting, independently for each period, the location with the highest likelihood. To assess

the realism of this trajectory, we compared it qualitatively to published tracks of Eurasian Bee-eaters and Alpine Swifts from a similar breeding area (Dhanjal-Adams et al., 2018; Meier et al., 2020). These published tracks were generated by a Bayesian movement model that uses light data and assumed flight speed distributions to more accurately reflect bird migration patterns.

3 | RESULTS

3.1 | Assessment of magnetic and light geolocation

We assessed the spatial accuracy of magnetic inclination, magnetic intensity and light-only geolocation estimates against the reference trajectories across 1'546 stationary periods (Figure 2). Supporting Information 1 contains interactive figures for each step of the process for all individual tags. Median spatial deviations were 135 km for inclination (IQR: 67–267 km), 334 km for intensity (IQR: 160–650 km), 468 km for light-level latitude (IQR: 192–1'158 km) and 137 km for light-level longitude (IQR: 57–274 km). Magnetic inclination was significantly more precise than magnetic intensity, with median deviations approximately 2.5 times smaller (paired Wilcoxon signed-rank test, $p < 0.001$). Because these distances are computed relative to a model-based reference, part of the observed deviation may reflect uncertainty in the reference itself rather than magnetic parameter estimation error alone.

Magnetic likelihood maps primarily provide latitudinal information across the flyway of our study species (see Figure 1), so distances to magnetic-based positions can be interpreted as roughly latitudinal deviations. In our study area, magnetic inclination provided little information along longitude, but magnetic-based latitude estimates were substantially more precise than those derived from light, reducing median deviation by approximately 3.5-fold (135 km vs. 468 km). This latitudinal precision is comparable to that of light-level geolocation along longitude (median deviations 135 km vs. 137 km).

These patterns were consistent across all five species, although absolute deviations varied slightly, while the relative spatial precision among methods remained the same (Figure 3a). Light-based latitude deviation decreased substantially with longer stationary periods (Spearman's $\rho = -0.19$), reflecting the need for multiple twilight events to average out behavioural and environmental noise (see Figure 3b). In contrast, magnetic-based deviation showed little sensitivity to duration ($\rho = -0.07$ for inclination, -0.03 for intensity), highlighting the robustness of magnetic geolocation even for short stationary periods.

3.2 | Aerial species

We compared the reconstructed migratory trajectories of Eurasian Bee-eaters and Alpine Swifts using light-only (longitude and latitude), magnetic-only (intensity and inclination) and combined geolocation approaches (Figure 4).

Light-based trajectories showed strong longitudinal consistency but poor latitudinal precision, often shifting entire migration routes latitudinally along a narrow meridian. In contrast, magnetic inclination and intensity produced realistic latitudinal positions, but with considerable east–west uncertainty reflecting weak longitudinal gradients in the Earth's magnetic field. Notably, magnetic intensity showed a northwest–southeast uncertainty in the Bee-eater's southern positions, mirroring the orientation of magnetic intensity isolines in this area. Note that the light method can retrieve the position of the non-breeding stationary location (in both latitude and longitude) because of its long duration, whereas intensity and inclination fail to narrow down longitude estimates even for such long time series.

The joint approach substantially improved estimated trajectories, reconstructing biologically plausible north–south and east–west movements that aligned well with known migratory corridors and seasonal distributions for both species (Dhanjal-Adams et al., 2018; Hahn et al., 2020; Meier et al., 2020). In particular, the joint likelihood captured two key Bee-eater stopover sites, visible as clusters of small white dots in the last column of Figure 4, in North Africa (Algeria/Tunisia) and West Africa (Benin), as well as overwintering regions in Central Africa for Bee-eaters and in East Africa for Alpine Swifts.

4 | DISCUSSION

4.1 | Methodological strengths and complementarity with existing approaches

In this study, we show that three-axis magnetic data from multi-sensor geolocators deployed on birds can be used to estimate positions along migratory journeys, achieving a typical latitudinal precision of 135 km (IQR: 67–267) relative to model-based reference trajectories. Because these distances are calculated relative to a probabilistic reference trajectory, part of the observed deviation likely reflects uncertainty in the reference itself rather than error in the magnetic estimates alone. The Earth's magnetic inclination varies predominantly with latitude, while intensity exhibits more complex spatial patterns but generally also changes latitudinally over most migratory flyways (NOAA NCEI Geomagnetic Modeling Team & British Geological Survey, 2024a). Accordingly, magnetic-based positions are best interpreted as latitudinal estimates, which is particularly useful given that most flyways of migratory animals follow a north–south orientation. This approach can, for example, help determine the timing of major barrier crossings such as the Mediterranean Sea and the Sahara Desert for aerial species (see illustration in Figure 4) that have so far been largely excluded from studies of barrier-crossing strategies (e.g. Dufour et al., 2024).

Because magnetic-based positions primarily estimate latitude, they are most powerful when paired with complementary light-level geolocation. Indeed, light-based methods offer high precision along longitude but suffer from poor latitudinal precision around

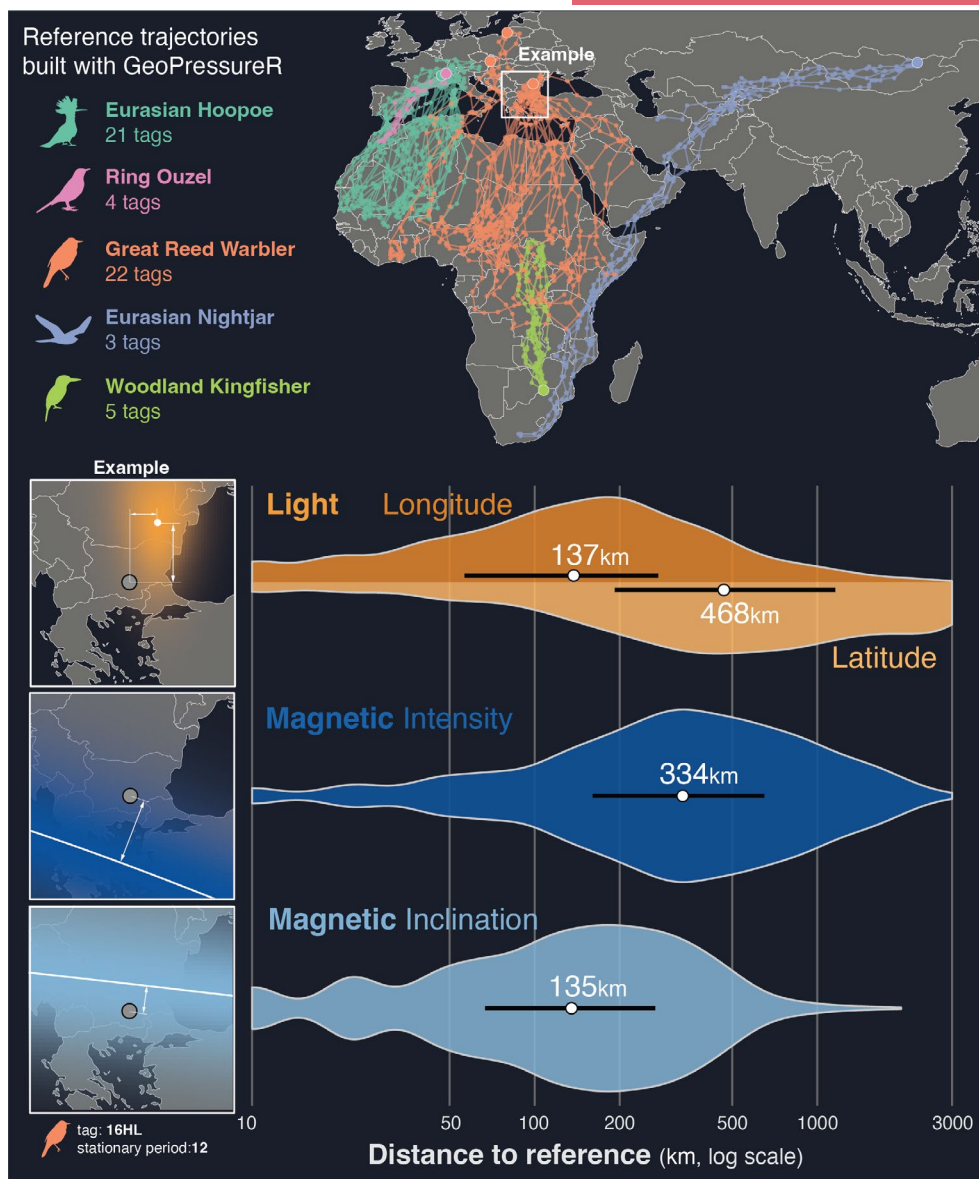


FIGURE 2 Comparison of spatial accuracy of light- and magnetic-based geolocation methods using the trajectories reconstructed by the GeoPressureR pipeline as reference. Top: Map illustrating migration trajectories comprising 1'546 stationary periods from 55 tags and across five species used in this comparison. Each dot represents the most likely position of a stationary period based on pressure, acceleration and wind data (GeoPressureR movement model). These positions are thereafter used as references for the comparison. Bottom-left: Illustration of the distances computed with a single stationary period of a Great Reed Warbler as an example. The grey dot shows the GeoPressureR reference position, and arrows show the distance to the most likely positions derived from the likelihood maps of light-level geolocation (top), magnetic intensity (middle) and magnetic inclination (bottom). Bottom-right: Violin plots showing the distribution of distance (log-scale) from reference location to the most likely position estimated for light-only (latitude and longitude), and magnetic intensity and magnetic inclination likelihood maps for all 1'546 stationary periods. The dot indicates the median, and the line represents the interquartile range (25th–75th percentile).

equinoxes that coincide with peak bird migration season and near the equator due to day-length symmetry (Fudickar et al., 2012; Lisovski et al., 2012). The orthogonality of these two information sources enables joint inference frameworks in which magnetic data resolve latitude while light data refine longitude. Additionally, incorporating a movement model (e.g. Nussbaumer, Gravey, Briedis, Liechti, & Sheldon, 2023; Rakhimberdiev et al., 2015; Sumner et al., 2009) could further refine reconstructed trajectories by

imposing biologically realistic constraints on possible travel speeds, representing a promising avenue for future analyses not explored in the present work.

Magnetic-based geolocation is especially valuable for species in which pressure-based localisation is unreliable such as non-stop flyers and aerial foragers (Nussbaumer, Gravey, Briedis, & Liechti, 2023; Rhyne et al., 2024). It is also particularly relevant for aquatic species, such as fish that spend most of their time underwater, and for which

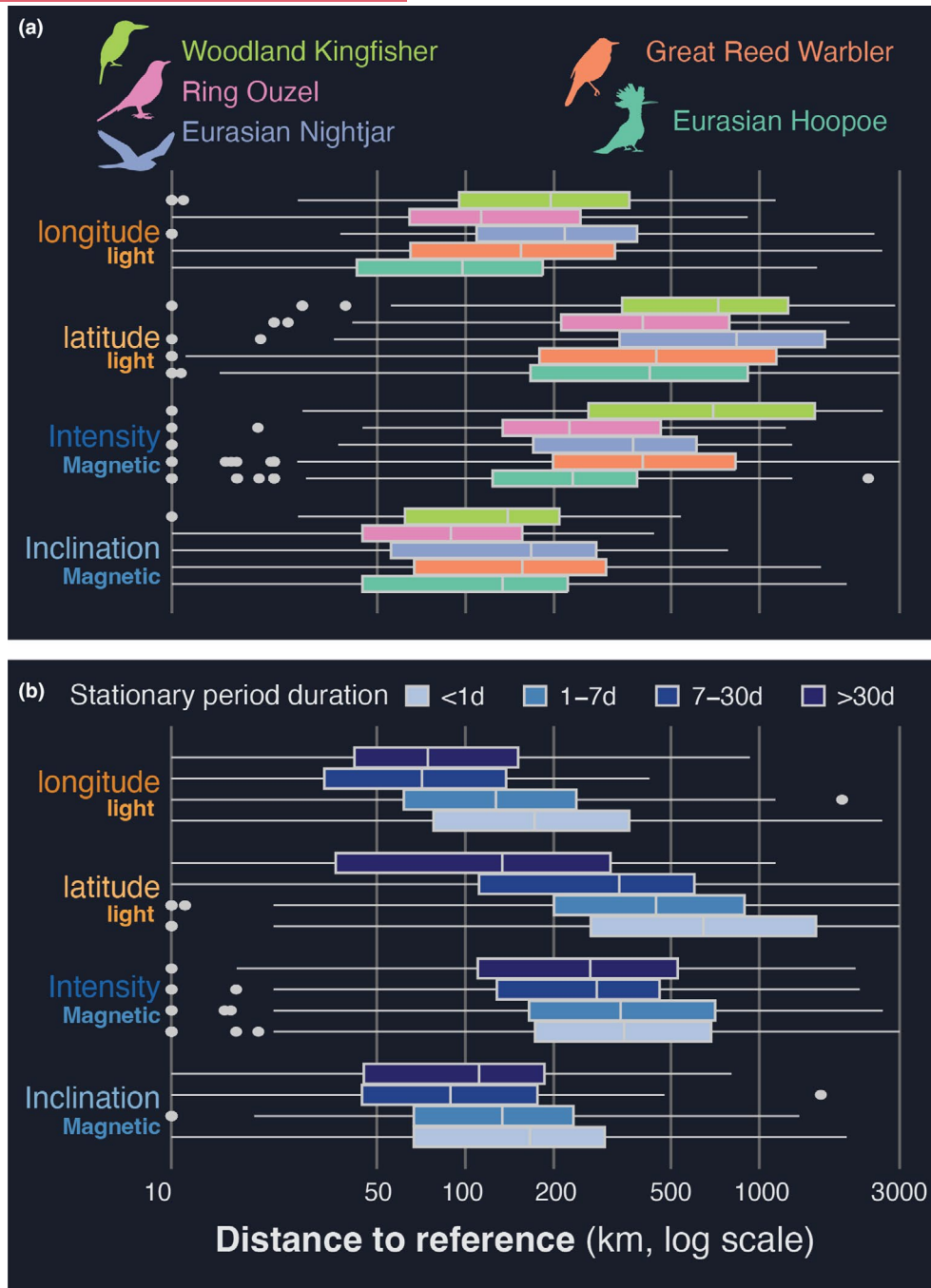


FIGURE 3 Boxplot of the same distribution of distance as in Figure 2 but grouped by species (a) and stationary period duration (b). Boxes represent the interquartile range (25th–75th percentile); the vertical line inside the box indicates the median, whiskers extend to $1.5 \times \text{IQR}$ and individual dots represent outliers.

geolocation, hitherto, has typically relied on light, salinity or temperature (Nielsen & Sibert, 2007; Pedersen et al., 2008; Thygesen et al., 2009), but for which magnetic data have already been collected (e.g. Noda et al., 2014). For these groups, a combination of light and magnetic data may represent the best viable geolocation method. Even when pressure data are available, magnetic data can improve localisation during short stationary periods, especially those preceded and followed by long flights, where topography is flat or around the equator, where variation of atmospheric pressure

is weak. In these scenarios, a notable strength of magnetic-based geolocation is that a single instantaneous measurement can suffice to estimate latitudinal position.

4.2 | Limitations and potential improvements

Improving the spatial accuracy of magnetic geolocation primarily depends on better characterizing and reducing observation-level

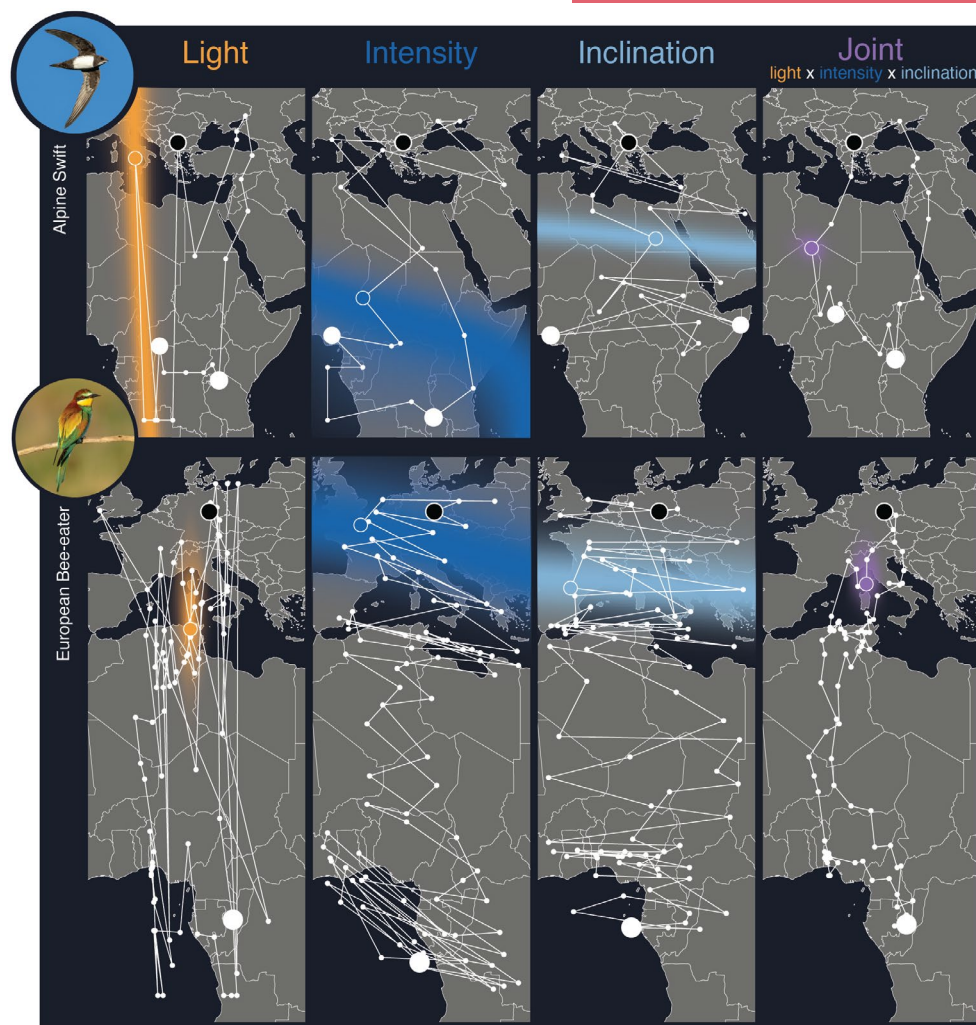


FIGURE 4 Comparison of migratory trajectories reconstructed for two individuals of aerial species: The Alpine Swift (top row) and the Eurasian Bee-eater (bottom row) using likelihood maps derived from (1) light-level geolocation, (2) magnetic intensity geolocation, (3) magnetic inclination geolocation and (4) the joint likelihood, built as the product of the first three. The trajectories are displayed as a white line connecting the breeding site (black circle), daily positions during migration (small white circles) and the non-breeding stationary site (large white circle). Each trajectory is built using, independently for each stationary period, the location corresponding to the highest value of the likelihood map. This is illustrated for a single randomly selected stationary period in both species, with the underlying likelihood map (colour gradient) and most likely position (coloured circles). The joint maps demonstrate that integrating the light and magnetic likelihoods substantially decreases uncertainty in both latitude and longitude, yielding a more credible trajectory. Photos: Marcel Burkhardt.

uncertainty. In our framework, this uncertainty is captured empirically by the error terms of the likelihood model, which combine residual sensor noise, imperfect calibration, environmental effects and any remaining mismatch between observed magnetic values and the reference trajectories used for evaluation. Across species, these empirical error terms were typically several degrees for inclination and around 0.01 G for intensity (Appendix B), substantially larger than short-term geomagnetic variation and the nominal uncertainty of the WMM (Appendix C). Consequently, improving calibration procedures and identifying the sources of residual measurement variability are likely to provide the largest gains in geolocation accuracy.

A key limitation lies in the calibration of magnetic sensors. Standard laboratory calibration proved unreliable for lightweight geolocators, likely because battery configuration, tag assembly

and mounting can alter local magnetic interference between calibration and deployment. We therefore relied on a field-based calibration approach that does not require dedicated calibration procedures and can be applied retrospectively to existing datasets. While robust and broadly applicable, this approach depends on sufficient variation in body orientation and geographic sampling, and may therefore be sensitive to species behaviour and movement patterns (Appendix A). Further improvements in calibration methodology, including better separation of sensor noise from environmental variability, should translate directly into more precise estimates of inclination and intensity. Occasional transient offsets, potentially linked to battery discharge or temperature effects, suggest that time-varying calibration could reduce bias,

while improved tag design and shielding may further reduce electromagnetic noise.

Refinements in geomagnetic reference data are therefore unlikely to substantially improve geolocation accuracy until measurement uncertainty is reduced. The WMM provides global predictions of inclination and intensity with typical uncertainties of $\sim 0.2^\circ$ and ~ 0.0014 G, respectively (NOAA NCEI Geomagnetic Modeling Team & British Geological Survey, 2024a). These uncertainties are smaller than the empirical variability observed in calibrated tag data, although they are not negligible in absolute terms. Moreover, Appendix C shows that temporal geomagnetic variation and the error introduced by evaluating WMM at a single representative date are minor compared with logger-level variability, and are effectively absorbed by the empirical error structure of the likelihood model. Higher-resolution geomagnetic products such as WMMHR (NOAA NCEI Geomagnetic Modeling Team & British Geological Survey, 2024b), or models incorporating local magnetic anomalies, may improve spatial resolution in some regions, but their contribution is currently limited by the dominant measurement noise. Similarly, explicitly modeling short-term geomagnetic disturbances would likely provide only marginal benefits under current sensor precision.

4.2.1 | Outlook: Expanding the scope beyond geolocation

Beyond its role in geolocation, magnetic data have proven useful for various ecological applications, particularly for behavioural classification; for example, to assess foraging activity (Chakravarty et al., 2019; Demšar et al., 2025; Schoombie et al., 2023; Williams et al., 2017). However, these applications have so far been largely restricted to mammals, large seabirds or raptors (Angelakis et al., 2023; Conners et al., 2021; Williams et al., 2015). Extending these methods to small migratory birds holds promise for uncovering new insights into energy expenditure, stopover behaviour and foraging strategies throughout migration. Importantly, the methodological approach outlined in this study, particularly the novel field-data calibration, provides a solid foundation for extracting meaningful variables to support these analyses. To fully realise these benefits, a substantial increase in sampling rate, from the 3–6 h of the sensors used in this study to less than 15 min, is essential for enhancing the temporal resolution and precision of behavioural assessments.

Moreover, by combining three-axis magnetic and acceleration data, we can accurately determine a bird's heading, especially during flight. This information would allow us to differentiate between migratory and foraging flights in aerial feeders and would be crucial for studying wind-drift compensation, as it reveals how birds adjust their flight direction relative to wind conditions. Such data would also enable testing hypotheses related to clock-and-compass orientation, goal-oriented navigation and true navigation mechanisms in migratory birds, since they are known to make use of magnetic field information in orientation and navigation (Packmor et al., 2024; Wiltschko & Wiltschko, 2019). Importantly, our approach represents

the first opportunity to assess these behaviours in free-flying songbirds over entire migratory trajectories.

AUTHOR CONTRIBUTIONS

Raphaël Nussbaumer: Conceptualisation, methodology, software, formal analysis, visualisation, writing original draft. Erich Bächler: Investigation, methodology (sensor development and testing), review and editing. Felix Liechti: Conceptualisation (initial idea of magnetic sensor integration)—review and editing. Others: Writing—review and editing. Barbara Helm: Conceptualisation, supervision, review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

GeoMagR R package (Nussbaumer, 2025): The R package used for magnetic-field data processing and likelihood-map generation, including the functions `geomag_calib()` and `geomag_map()`, is publicly available from GitHub at <https://github.com/geopressure/GeoMagR>, with package documentation available at <https://geopressure.org/GeoMagR/> and archived on Zenodo at <https://doi.org/10.5281/zenodo.19217142>. Project data and analysis code (Nussbaumer, 2026): The data and code used to generate the analyses and results presented in this paper are archived on Zenodo and available at <https://doi.org/10.5281/zenodo.19497391>. Geolocator

datasets: The five geolocator datasets used for the accuracy assessment are publicly available as geolocator data packages cited in this article: Barras et al. (2025), Lathouwers et al. (2025), Nussbaumer et al. (2025), Rime, Briedis, et al. (2025) and Schaub et al. (2025).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix A. Insitu calibration of magnetometers using stationary periods.

Appendix B. Estimation of likelihood model parameters.

Appendix C. Temporal variability of the geomagnetic field and adequacy of the World Magnetic Model (WMM).

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