Investigating geomagnetic bird navigation: 4D data fusion of co-located GPS and magnetometer data

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Abstract

Co-located sensors are becoming standard in animal movement ecology, yet measurements they produce are often underused due to the lack of methods that would allow these measurements to be integrated with locational information. In this paper we propose an algorithm for 4D data fusion of co-located GPS and magnetometer data. Magnetometers measure the Earth's magnetic field, which has been shown to be one of the cues that long-distance migratory birds use for navigation. A magnetometer on a tracking tag collects data in a coordinate frame that is fixed to the body of the bird, but constantly changes orientation with the movement of the bird. Locational information on the same tag is however typically collected in an Earth-based coordinate frame. Using the information from both GPS and magnetometer we propose an algorithm for 4D transformation of magnetic measurements into the Earth-based frame, so that they can be used for analysis of behavioural movement responses to local magnetic conditions.

Keywords: Movement analytics, 4D, GPS, magnetometer, data fusion.

1 Introduction

Recent technological developments and miniaturisation of tracking devices have brought unprecedented possibilities for animal movement studies. Movement ecology suddenly finds itself in a big data situation where the new sensors allow more and more animal species to be tracked and data to be collected not only on position, but also on the characteristics of the environment at each moment in time. This opens a large potential for contextualising movement analytics and investigating animal responses to the particular environmental conditions, which is one of the fundamental questions in movement ecology. However, methods for analysing these new complex data are struggling to keep up with data acquisition innovations. This is particularly the case for new sensors that produce new complex types of data, one of which are magnetometers, which measure the Earth's magnetic field.

Tri-axial magnetometers are becoming standard on animal tracking tags. The measurements they produce are time series of the Earth's magnetic field vector, decomposed into three coordinate axes of a coordinate system that is fixed onto the body of the animal. That is, the three axes point into the direction of the head of the animal, across its shoulders and perpendicular to the shoulders. This configuration is excellent for posture analysis, and, often combined with accelerometery, allows ecologists to distinguish between specific posture-related movement behaviours (Williams et al., 2018).

However, precisely because the magnetic measurements are linked to the body-based coordinate system that constantly changes its position and orientation in the 3D physical space, they cannot be in their raw form used for identification of animal's responses to the changes in strength and direction of the Earth's magnetic field, something that is very important for study of migratory birds.

Migratory birds make journeys that cross oceans, deserts and mountain ranges, navigating between their specific breeding and wintering areas. The ability that they use for this and which we still don't understand fully is the migratory true navigation: the ability to navigate to a specific breeding or wintering area far away and in an unfamiliar location using only cues detected locally (Holland, 2014). A number of strategies have been proposed for true navigation, using different types of compasses (a Sun, stars, polarised light and magnetic compass), olfactory cues, natural infrasound (such as the sound of waves crashing on the shore) and visual cues (Wikelski et al., 2015, Åkesson and Bianco, 2016). In this paper we focus on geomagnetic navigation, that is, navigation that uses the information from the Earth's magnetic field as the primary cue.

Bird tracking studies that investigate geomagnetic navigation typically use tags with several co-located sensors, each of which collects data at different temporal schedules and sampling rates. This poses a problem for analysis, since data from different sensors are not temporally synchronised. Fusing these data is therefore a necessary first step.

An additional complication is that long-distance migration is one of the movement types that is distinctly three-dimensional. Unlike when staying at breeding or wintering sites, birds soar to high elevations to make use of different conditions in different layers of the atmosphere (Treep et al., 2016). This means that any location data collected during migration need to include elevation.

Further, the coordinate frame of these 3D locational measurements is Earth-based, either consisting of geographic coordinates (latitude, longitude, elevation) or projected coordinates using a particular projection. In contrast to the body-based coordinate system that magnetometers use, this system does not change with the movement of the bird. This introduces an additional problem to integration of data from different sensors: not only are they collected asynchronously, but also in different coordinate systems, one of which constantly changes with the movement of the bird. While solutions for this type of problem exist in for example UAV navigation, in movement ecology there is a lack of data fusion methods for complex 4D data (Demšar and Long, 2019).

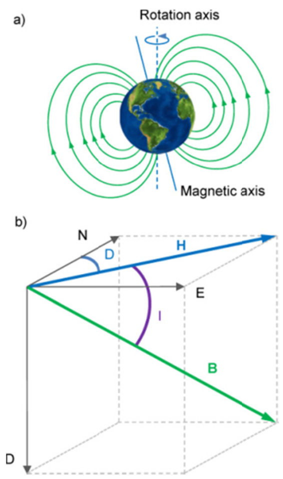
In this paper we propose an algorithm for data fusion of locational and magnetometer data as a first necessary step to support data-driven investigations of geomagnetic bird navigation. We address the problem of non-synchronicity of data collection by co-located GPS and magnetometer sensors and take inspiration in spacecraft and aircraft attitude determination to solve this problem.

2 Methods

2.1 Earth's magnetic field and bird navigation

Earth's magnetic field is a constantly fluctuating combination of the core field generated by the dynamo mechanism of the outer liquid core of the Earth, the lithospheric field created by the magnetic properties of the rocks in the Earth's crust and the external effects caused by interactions with the Sun's and interplanetary magnetic fields (Campbell, 2003). Field lines connect the two magnetic poles, which are at an offset from the geographic poles (Figure 1a). The field is typically measured in an Earth-based coordinate system, where the magnetic field vector **B** is decomposed along the North-East-Down axes (NED, this is an unusual configuration for geographers, but is necessary to create a right-handed observation system). The length of the vector **B** is called the intensity of the field, the angle between **B** and its horizontal component **H** is called the inclination I or sometimes the dip angle and the angle between H and the geographic north is called the declination D.

Figure 1: a) Earth's magnetic field. b) Magnetic field vector **B** at a particular location on the surface of the Earth is measured in the Earth-based NED (North/East/Down) coordinate system. **H** is the horizontal component of **B**, parallel to the Earth's surface. *I* is the inclination and *D* is the declination.



Migratory birds have been shown to be able to sense both the inclination and the intensity of the field (Holland, 2014). There is however no consensus how exactly they use these values for their long-distance navigation.

2.2 Animal movement data: GPS and magnetometry

Tracking tags for migratory birds are deployed for long-term periods (over several years), which means that sampling rates of different sensors vary, depending on the type of observation and battery life. A typical set-up is that the GPS sensor collects information at a sparser sampling rate (e.g. every 30 min) than the magnetometer (e.g. every 10 min). The magnetometer also collects the information in short bursts, and at each burst creates a time series of measurements of **B** in each of the three body-based directions, for example 5-10 measurements, one per second. In this paper we assume that we only have one measurement of **B** at each burst and call that $\mathbf{B}_{raw}$, which is a representation of the Earth's magnetic field in the body-based system of the bird at a particular moment in time (Figure 2). $\mathbf{B}_{raw}$ can be calculated by averaging the values across the burst time series.

We further assume that the GPS location is observed in a fixed Earth-based NED system. To simplify calculations, we assume that this is a projected coordinate system, where the elevation axis is reversed to point downwards. We introduce this convention to be able to validate our method in the future with external magnetic field measurements (e.g. from terrestrial networks or satellite observations), that come in the NED frame.

The problem that we are trying to solve is how to transform $\mathbf{B}_{raw}$ from the body-based coordinate system into the Earth-based NED system at a particular location in space and time. The goal is to be able to calculate the two specific magnetic properties (intensity and inclination), which are crucial for any analysis of bird navigation strategies.

2.3 Calculating $\mathbf{B}_{NED}$: rotating the body-based system into the Earth-based system

To be able to calculate the transformation between the two coordinate systems, we adopt ideas from attitude determination, which is the calculation of the orientation of a body with respect to a fixed coordinate system (Markley and Crassidis, 2014). For this, we look at the orientation of the bird as derived from GPS data and calculate the navigation angles (yaw, pitch and roll) which define the transformation from the fixed frame into the body-based frame. To derive $\mathbf{B}_{NED}$ we then reverse-rotate $\mathbf{B}_{raw}$ in the opposite direction.

We assume that the body-position of the bird between two GPS positions roughly corresponds to a linear line between the two 3D points. This is not an unreasonable assumption for long-distance migratory flight: during these flights birds often fly very fast and follow a relatively direct line (Åkesson and Bianco, 106).

Figure 2: Acquisition of GPS and magnetometry data. GPS tag collects 3D locations at points $\mathbf{P_i}$ at regular time intervals. Coordinates of these points are given in a fixed Earth-based x,y,z system, where we followed the convention of magnetism and these correspond to North, East and Down respectively. Magnetometer on the tag is not synchronised with the GPS and collects data at different times, resulting in magnetic points $\mathbf{M_j}$. At each of these points the local magnetic field vector **B** (shown in green) is measured in the dynamic coordinate system (shown in grey), which is fixed to the body of the bird and consists of the yaw, pitch and roll axes. The coordinates of **B** in this system are given as the $\mathbf{B_{raw}}$ vector. The size and direction of the magnetic field **B** also vary with location (e.g. between M_4 and M_5), adding additional complexity.

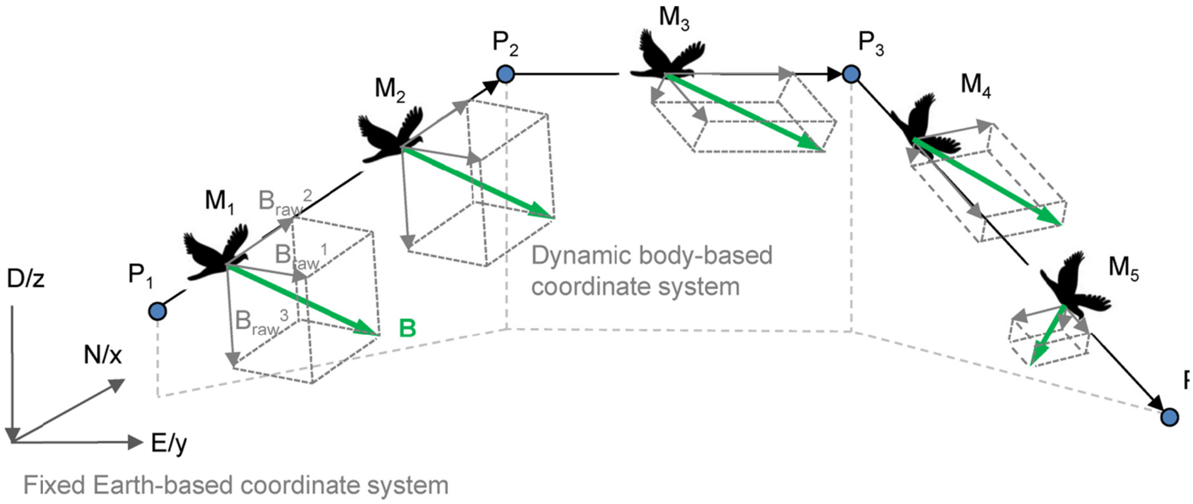
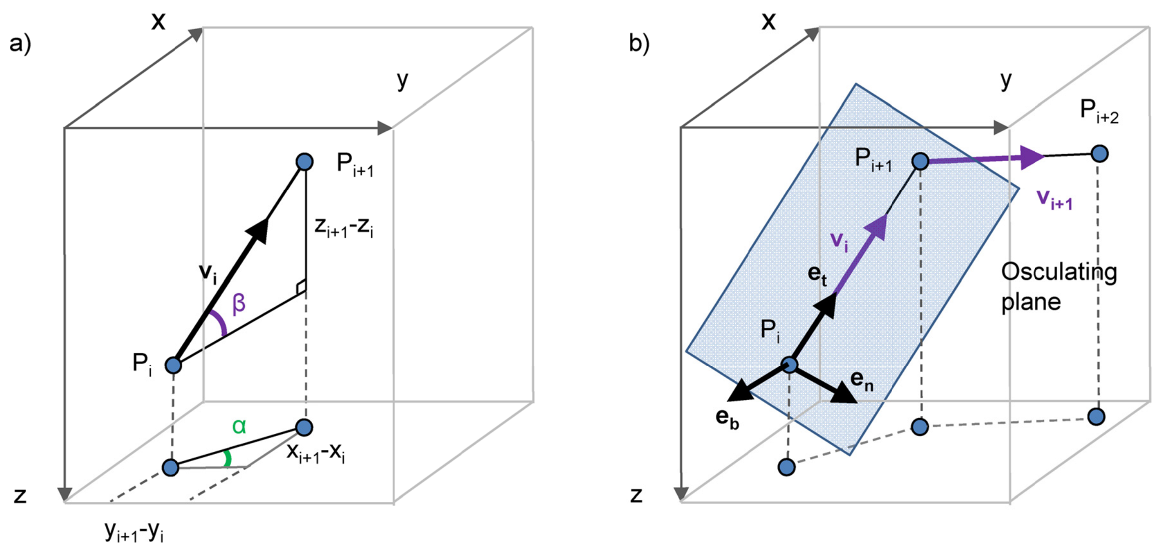


Figure 3: a) Derivation of the navigation angles α (yaw) and β (pitch) from the position of two consecutive GPS points $\mathbf{P_i}$ (x_i,y_i,z_i,t_i) and $\mathbf{P_{i+1}}$ (x_{i+1}, y_{i+1}, z_{i+1}, t_{i+1}). The velocity vector $\mathbf{v_i}$ points in the direction of travel and is rotated for angle α on the horizontal plane and angle β on the vertical plane. b) The third navigation angle γ (roll) is not shown, but is calculated by separating the acceleration vector into the tangential ($\mathbf{e_t}$) and normal ($\mathbf{e_n}$) components of velocity on the osculating plane – the plane that locally contains the trajectory. The tangent ($\mathbf{e_t}$) is the current direction of velocity; the normal ($\mathbf{e_n}$) is the perpendicular direction into which the velocity is changing (e.g. direction from $\mathbf{v_i}$ to $\mathbf{v_{i+1}}$); the binormal ($\mathbf{e_b}$) points out of the osculating plane and is not relevant, but is included for clarity.



Given the two consecutive GPS points $\mathbf{P_i}$ (x_i,y_i,z_i,t_i) and $\mathbf{P_{i+1}}$(x_{i+1}, y_{i+1}, z_{i+1}, t_{i+1}), we can calculate the yaw α and the pitch β (Figure 3a) using the following equations:

$$\alpha = \arctan\left(\frac{x_{i+1} - x_i}{y_{i+1} - y_i}\right) \tag{1}$$

$$\beta = \arcsin\left(\frac{z_{i+1} - z_i}{d(\boldsymbol{P}_i, \boldsymbol{P}_{i+1})}\right) \tag{2}$$

where d($\mathbf{P_i}$,$\mathbf{P_{i+1}}$) is the 3D distance between the two points:

$$d(\boldsymbol{P}_i, \boldsymbol{P}_{i+1}) = \sqrt{(x_{i+1} - x_i) + (y_{i+1} - y_i) + (z_{i+1} - z_i)} \tag{3}$$

To calculate the roll γ we use velocity vectors $\mathbf{v_i}$ and $\mathbf{v_{i+1}}$ at two consecutive GPS positions, for which we need three consecutive locations $\mathbf{P_i}$, $\mathbf{P_{i+1}}$ and $\mathbf{P_{i+2}}$ (Figure 3b):

$$\boldsymbol{v}_j = \frac{\boldsymbol{P}_{j+1} - \boldsymbol{P}_j}{t_{j+1} - t_j}, j = i, i+1 \tag{4}$$

From this, we can calculate acceleration $\mathbf{a_i}$ as:

$$\boldsymbol{a}_i = \frac{\boldsymbol{v}_{i+1} - \boldsymbol{v}_i}{t_{i+1} - t_i} \tag{5}$$

In attitude determination, acceleration is separated into two vectors that define the osculating plane, that is the plane that locally contains the trajectory (Figure 3b) and is defined by the tangential and normal directions of $\mathbf{v_i}$. This gives us:

$$\boldsymbol{a}_i = \boldsymbol{a}_i^t + \boldsymbol{a}_i^n \tag{6}$$

where *t* and *n* denote the tangential and normal direction (i.e. directions of vectors $\mathbf{e_t}$ and $\mathbf{e_n}$ in Figure 3b). They are calculated as per this:

$$\boldsymbol{a}_i^t = \frac{\boldsymbol{a}_i \cdot \boldsymbol{v}_i}{|\boldsymbol{v}_i|^2}\ \boldsymbol{v}_i \tag{7}$$

$$\boldsymbol{a}_i^n = \boldsymbol{a}_i - \boldsymbol{a}_i^t \tag{6}$$

Similarly, the gravitational acceleration $\mathbf{g}$ = (0,0,g_0), where g_0 = 9.81 m/s^2, can be separated in the same directions:

$$\boldsymbol{g}^t = \frac{\boldsymbol{g} \cdot \boldsymbol{v}_i}{|\boldsymbol{v}_i|^2}\ \boldsymbol{v}_i \tag{9}$$

$$\boldsymbol{g}^n = \boldsymbol{g} - \boldsymbol{g}^t \tag{10}$$

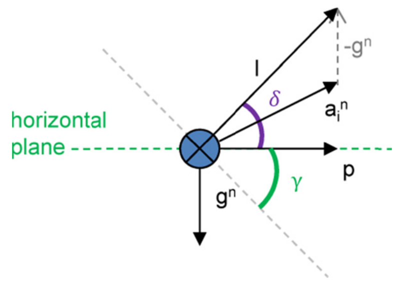
In aircraft attitude determination (Kornfeld et al., 1998), the normal component of the acceleration is equal to the sum of the lift acceleration vector $\mathbf{l}$ and the normal component of gravity $\mathbf{g^n}$ (Figure 4):

$$\boldsymbol{a}_i^n = \boldsymbol{l} + \boldsymbol{g}^n \tag{11}$$

We can define the horizontal reference vector $\mathbf{p}$ as a vector product of the normal component of $\mathbf{g}$ and $\mathbf{v_i}$ (Figure 4):

$$\boldsymbol{p} = \boldsymbol{g}^n\ \boldsymbol{x}\ \boldsymbol{v}_i \tag{12}$$

Figure 4: The definition of the roll angle *γ*. The $\mathbf{v_i}$ points out of the page on this figure. The lift acceleration $\mathbf{l}$ is the normal acceleration $\mathbf{a_i^n}$ minus the gravitational acceleration $\mathbf{g^n}$. Vector $\mathbf{p}$ is the reference vector on the horizontal plane and is used to define the roll angle *γ*, which is the complementary angle to angle *δ* between $\mathbf{l}$ and $\mathbf{p}$.



Then, the roll γ is the complementary angle of the angle δ, which is the angle between $\mathbf{l}$ and $\mathbf{p}$. δ and γ are given as:

$$\gamma = \arcsin\left(\frac{\boldsymbol{l} \cdot \boldsymbol{p}}{|\boldsymbol{l}| \cdot |\boldsymbol{p}|}\right), \qquad \delta = \arccos\left(\frac{\boldsymbol{l} \cdot \boldsymbol{p}}{|\boldsymbol{l}| \cdot |\boldsymbol{p}|}\right) \tag{13}$$

The rotation of the Earth-based system into the body-based system is then given by the rotation matrix *R(α,β,γ)* in this order, that is, we first rotate for angle α around z axis, then for β around y axis and then around γ around x axis. *R(α,β,γ)* is a product of three rotation matrices, one for each angle, in the opposite order, to account for the order of rotations: *R(α,β,γ)=R(γ) · R(β) · R(α)*. For the inverse rotation, that is, to obtain $\mathbf{B_{NED}}$ from $\mathbf{B_{raw}}$, we need to switch the order and the direction of rotation. We therefore rotate with the matrix *R(-γ,-β,-α)= R(-α) · R(-β) · R(-γ)*, where:

$$\mathrm{R}(-\alpha) = \begin{bmatrix} \cos(-\alpha) & \sin(-\alpha) & 0 \\ -\sin(-\alpha) & \cos(-\alpha) & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

$$\mathrm{R}(-\beta) = \begin{bmatrix} \cos(-\beta) & 0 & -\sin(-\alpha) \\ 0 & 1 & 0 \\ \sin(-\beta) & 0 & \cos(-\beta) \end{bmatrix}, \tag{14}$$

$$\mathrm{R}(-\gamma) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(-\gamma) & \sin(-\gamma) \\ 0 & -\sin(-\gamma) & \cos(-\gamma) \end{bmatrix}.$$

Finally:

$$\boldsymbol{B}_{NED} = R(-\alpha) \cdot R(-\beta) \cdot R(-\gamma) \cdot \boldsymbol{B}_{raw} \tag{15}$$

2.4 Creating the magnetic trajectory: the algorithm

We can use the derivation from the previous section to create a semantically annotated magnetic trajectory where the two magnetic properties that the birds can sense (inclination and intensity) are calculated for each location. We do this for each timestamp in magnetic data $\mathbf{M_j}$ (Figure 3b) and perform the following calculations at each $\mathbf{M_j}$:

Step 1: Identify the $\mathbf{P_i}$, $\mathbf{P_{i+1}}$ and $\mathbf{P_{i+2}}$ GPS points, such that point $\mathbf{M_j}$ is time-wise located between $\mathbf{P_i}$ and $\mathbf{P_{i+1}}$.

Step 2: Interpolate the location of the $\mathbf{M_j}$ point. As this is long-distance migration flight, we assume a direct straight flight between $\mathbf{P_i}$ and $\mathbf{P_{i+1}}$ and linearly interpolate through time to find the location of $\mathbf{M_j}$ on the line between $\mathbf{P_i}$ and $\mathbf{P_{i+1}}$. We note that other interpolations are possible for other types of movement (Long, 2015).

Step 3: Calculate $\mathbf{B_{NED}}$ from $\mathbf{B_{raw}}$ at $\mathbf{M_j}$ (equations 1-15).

Step 4: Calculate the intensity B_I and the inclination I from B_{NED} at $\mathbf{M_j}$ (Figure 1b):

$$B_{\mathrm{I}} = \sqrt{({B_{\mathrm{NED}}}^{\mathrm{N}})^2 + ({B_{\mathrm{NED}}}^{\mathrm{E}})^2 + ({B_{\mathrm{NED}}}^{\mathrm{D}})^2}\,, \qquad I = \arcsin\left(\frac{{B_{\mathrm{NED}}}^{\mathrm{D}}}{B_{\mathrm{I}}}\right) \tag{16}$$

The result is a semantically annotated trajectory which can be used as input into data mining (Brum Bastos et al., 2018) to investigate behavioural responses to magnetic conditions.

The algorithm is currently being implemented. Here we present the first results on simulated data: we created a GPS trajectory with simulated locations in 3D which were collected every 30 min at 1Hz in bursts lasting 2 minutes – the top panel in Figure 5a shows a time series of elevation in these simulated GPS data. We also generated simulated magnetic data with a 5s burst every 10 min in each of the three body-based directions (x,y,z), as shown in the bottom three panels in Figure 5a. Times of magnetic bursts did not coincide with times of GPS bursts and there was no locational information linked to the magnetic data. This is a fairly typical scenario in bird tracking, where GPS and magnetic tags are not interconnected and each is set on its own temporal data collection schedule. We then ran our algorithm to create a new magnetic trajectory consisting of interpolated 3D locations between GPS points that corresponded to times in magnetic data and where we calculated the intensity and inclination of the field. Figure 5b shows this trajectory, where colour on the magnetic trajectory indicates the magnetic intensity at each point. GPS bursts are shown in light green.

3 Conclusions and discussion

In this paper we introduced an algorithm for 4D data fusion of GPS and magnetometer data for bird movement analysis as work in progress. The mathematical concepts presented here are currently being implemented as an R package and will be made openly available. The algorithm will be tested on simulated data as well as on real data from wild migrants – we will focus on migrants to high latitudes where variability in magnetic field is the largest across short spatial and temporal scales. We will also evaluate the method against different sampling rates of GPS points – the further apart are these, the coarser the information on the attitude and orientation of migrating birds. An evaluation study with different sampling rates may lead to a recommendation to what is the optimum rate for GPS and magnetic data fusion, which the ecologists can then weigh against other factors, such as battery life.

With the introduction of a myriad new sensors, movement ecology is rapidly moving towards a new paradigm, where we can "see" the environment through the eyes and senses of the animals that humans do not possess. This "animals as sensors" concept has been successfully introduced in marine tracking, for example, elephant seals migrating around Antarctica and carrying oceanographic sensors act as moving platforms for collection of oceanographic data, which is crucial in the development of contemporary climate change models (Charrassin et al., 2008). Migrating birds have been used as meteorological observers of wind conditions over remove areas, such as the open ocean (Treep et al. 2016). However, magnetic bird-based measurements have not been considered in the same way. While the main goal of our work is to understand the mechanisms of the geomagnetic bird navigation, in the light of the poorly understood accelerated changes of the magnetic field (Witze, 2019), real-time magnetic bird data could also be used to improve our understanding of the dynamics of the Earth's magnetic field.

4 Acknowledgements

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Figure 5: Simulated data and results of our algorithm. a) Top panel shows the time series of elevation of the simulated GPS trajectory, where location was measured every 30 min for 2 min with 1Hz frequency. The other three panel show magnetic bursts collected each second for 5s at every 10 min. Panel b) shows how GPS and magnetic data are fused by creating a new magnetic trajectory, which is coloured with values of calculated magnetic intensity at each location on the new trajectory. Burst of GPS points sampled every 30 min are shown in light green.