MagGeo – A data fusion tool to link Earth's magnetic data from Swarm Mission to GPS trajectories

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Abstract

MagGeo is a data fusion tool that helps researchers link Earth's magnetic field data from satellites to GPS trajectories of tracked animals. This paper describes the technical process of combining geomagnetic data (from European Space Agency Swarm satellites) with animal tracking data using a new spatio-temporal interpolation method. The tool was developed in Python. This is the first tool of this kind, and we hope it can help ecologists better understand how wildlife respond to short-term variations on the geomagnetic field.

1. Introduction

Geomagnetic navigation is one of the migratory strategies and has been studied across several taxa (Mouritsen H, 2018). Many species of animals use the magnetic field to navigate, from birds (Deutschlander 2014, Wiltschko R 2015), fish (Naisbett-Jones LC 2017), sea turtles (Lohmann KJ 2007, Brothers JR 2018) to sea mammals (Granger J 2020, Vanselow H 2016). In laboratory experiments, the geomagnetic navigation has been studied by placing animals (Holland RA 2014, Wiltschko R 2015) in artificial magnetic field to determine what is its influence on direction at the onset of migration. This controlled environment provides precision over a limited number of individuals in most of cases from a single species, but it might vary from what can be experienced in the wild, where the Earth's magnetic field varies across both space and time. The variability across temporal scales that are relevant for animal navigation (from seconds to days) mostly comes from solar activity and may affect the potential animal's choice of direction during navigation. To date, ecologists were not able to study how these short-term field variations affect navigation, because of the lack of reliable geomagnetic data (Deutschlander 2014). Geomagnetic data at global scale have recently become available with the launch of the European Space Agency (ESA) satellites. These data however are complex: they are structured as three-dimensional time series of measurements taken at the location of each satellite with a fine temporal resolution. Linking these data to animal trajectories is therefore a challenging geometrical problem. This paper addresses this problem by developing a tool that will help ecologists obtain geomagnetic data at the location and time of the moving animal. Our tool, called MagGeo (https://github.com/MagGeo/MagGeo-Annotation-Program), is available as free and open-source software (FOSS) and uses a set of Jupyter notebooks to let users interact with the process. In this paper we describe the technical process of how we developed this tool (Benitez-Paez *et al.* 2021) which links wildlife tracking data with geomagnetic data provided from Swarm constellation.

2. Data fusion process

The data fusion process combines up-to-date geomagnetic data from a satellite mission that includes three satellites with wildlife trajectories collected in situ. The method annotates each tracked location with the variables that describe the state of the geomagnetic field at that location and moment in time. The tool requires two inputs: A given trajectory from a tracked animal, and geomagnetic data from the Swarm mission. For each track location, the method selects the nearest satellite measures (denominated as satellite points) in both space and time. With a spatio-temporal kernel our method selects only the feasible satellite points in space and time by initially calculating both the spatial distance between the tracked location and the selected satellite points as well as the temporal distance between the trajectory location timepoint and the filtered satellite data.

Earth's magnetic field is a combination of the core fields (generated by the Earth's outer core), lithospheric fields (generated by rocks in the Earth's crust) and the fields in ionosphere and magnetosphere, which are affected by the Solar wind. Of these, only the solar-wind affected fields change at time scales that could affect real-time migratory decision making. These fields vary at scales from seconds to hours and cannot be modelled, they need to be measured in situ. In Swarm data they are represented as residuals, which are the difference between the modeled core and crust fields and the unmodelled actual observations of the magnetic field captured at the orbital height. These short-term variations are only possible to measure using satellite sources and represent one of the advantages to apply our method instead of the replication of magnetic field in control laboratory experiments.

Magnetic data from each satellite point include these residuals structured in an Earth-based coordinate system where the intensity of the magnetic field **F**, is defined in tri-axial North-East-Centre (**NEC**) system (see Lanza et al. (2006) for more information about the geomagnetic components from the NEC reference frame). Once the satellite points are spatially and temporally filtered to get the nearest in space and time for each tracked point, our method applies a spatio-temporal Inverse Distance Weighted (ST-IDW) interpolation. The reason to apply an IDW approach for the interpolation process is because it will prioritize measurements from satellites points that are the nearest to the tracked locations in both space and time. We use residuals from all satellite points within the kernel to derive the value of residuals at the tracked point. Once this interpolation is done, these interpolated residuals are added onto the modelled values of the magnetic field (calculated using the CHAOS model, a time-dependent model based on terrestrial observatory and satellite measurements (DTU Space 2020), that is, the method will move the residuals from the orbital altitude to the altitude of the tracked animal. Once this is done, the result is the values of the geomagnetic field in the NEC directions at the location and time of the tracked point.

We further use these values to compute magnetic quantities which are normally used to describe the field: these include the Intensity-**F**, Declination-**D**, Inclination-**I** and the Horizontal component-**H**. We add several parameters for accuracy assessment to let the users evaluate the precision of the interpolation, including the number of and minimum distance of satellite points to the tracked point. This process is repeated for each point in the given trajectory.

The implementation of this method can be described in more details in the following in 5 steps:

Preparation - using the VirES web service to obtain Swarm data: VirES is a web-based service that enables scientists to download geomagnetic data from Swarm mission (European Space Agency 2021). Users of MagGeo will need a VirES token to get the data in bulk for the initial and final date of the given trajectory. VirES provides several data products. MagGeo will request MAGX_LR_1B (Magnetic data at low rate).

Step No 1: Obtain a unique list of dates of movement: Migratory trajectories usually have multiple records for the same date. Therefore, the method needs an initial selection of the unique dates included in the trajectory to avoid duplicating data download. MagGeo computes a list of unique dates which is the initial parameter for the download process. The given GPS trajectory requires at least four attributes, Latitude, Longitude, Altitude (optional), and the timestamp for each GPS point. To assure a selection of minimum two or three satellites we define a temporal window of +-4 hours around each GPS point. To guarantee that there are sufficient data across the midnight boundary at the start and end of the trajectory, the method requests one day extra when the GPS point time is less than 04:00:00 UTC or more than 20:00:00 UTC. With the unique list of days calculated based of the time of each tracked point, the method can now start the download process.

Step No 2: Download the geomagnetic values from Swarm satellites: The list of unique dates is the input parameter for the download process. MagGeo will loop through each date and request data from the three satellites in the Swarm mission. The data collected will contain, F as the Magnetic intensity at the satellite altitude, the geomagnetic residuals for the three components of the field in NEC reference frame, and data quality flags (F or B) for further data quality filters. As output in this step the process will create three time series with geomagnetic residuals components for all dates included in the unique list computed above.

Step No 3. Compute the Spatio-Temporal IDW interpolation (ST-IDW): The three time-series from the step No 2, and the initially given GPS trajectory are the input parameters for the ST-IDW process. The algorithm will first select the most appropriate satellite points based on 1) the spatio-temporal kernel and 2) data quality.

Spatio-temporal kernel: This process will filter spatially and temporally the satellite points for each GPS point. The time kernel selects all satellites points that are within +-4 hours of the given time in the trajectory point. The space-kernel is defined by two separate parameters 1) The distance between all previously filtered points and the trajectory point using the haversine formula (Robusto 1957) and 2) the radius of the circle within which MagGeo will be looking for the satellite points. This radius is based on the latitude of the trajectory point and is calculated so that it reaches 1800 kilometres at the Equator and 900km at the Poles (See figure 1A). The circle gets progressively smaller towards the Poles, since Swarm orbits are polar orbits that are closer to each other in the polar areas than at the Equator.

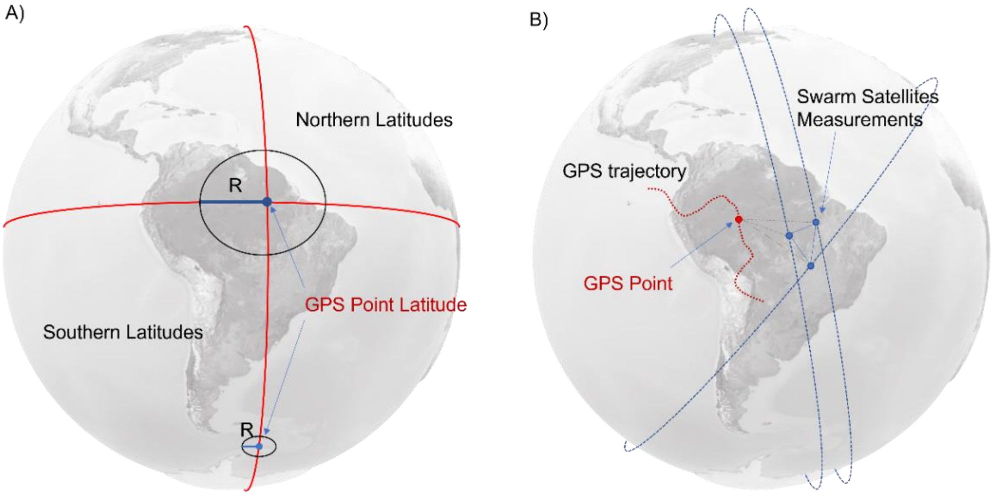

Figure 1. A). The spatial kernel is based on the GPS point latitude. B). The temporal kernel is based on the nearest Swarm measurements.

Remove inaccurate points for geomagnetic data quality: To provide accurate magnetic interpolations, all satellite points with magnetic intensity that exceed conventional values will be removed, and then using quality flags F and B captured in Step 2, we will include only satellite points considered as nominal, that is those measurements where there were no technical or maintenance reported issues with either the satellites or the instruments (European Space Agency 2021).

Inverse Distance Weighted Interpolation Process: At this point we interpolate residuals prioritising satellite points that are close to the GPS point in either space or time. For computing interpolation weights, the distances in time and space from the satellite points and the given GPS point, are normalized and inverted (see Figure 1B). Residuals at the GPS point location are then calculated as a weighted sum of residuals at satellite points. We use the inverse distance weights to interpolate residuals in all three axes (NEC) for the given GPS point. This process is repeated across all the points in the given GPS trajectory. Finally, the interpolated residuals are added to the modelled geomagnetic values at the GPS point (Figure 2), for this we use CHAOS-7 model, which is a time-dependent geomagnetic model based on satellite (Swarm, CryoSat-2, CHAMP, SAC-C and Ørsted) and terrestrial (INTERMAGNET network (INTERMAGNET 2021)) observations.

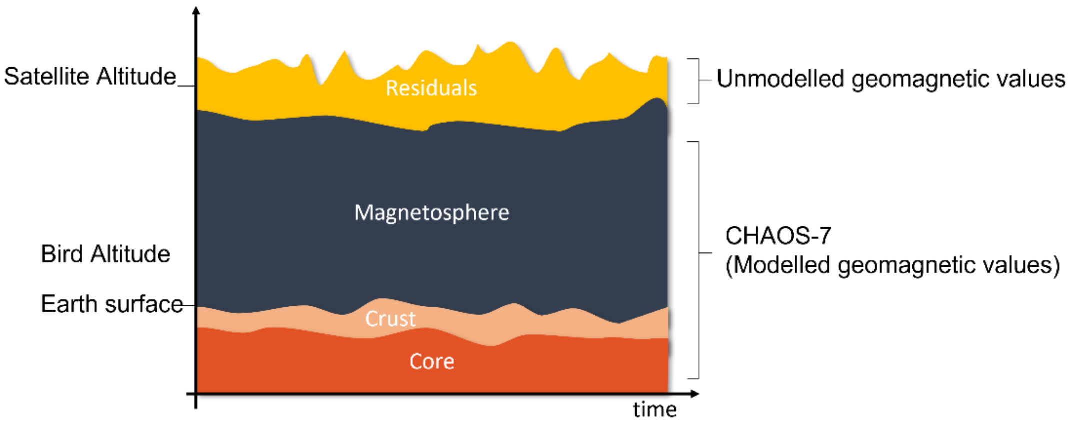

Figure 2. The residuals captured at the satellite altitude are added to modelled values from the CHAOS-7 model at bird altitude to calculate the high variability of the field.

Step No. 4. Accuracy assessment attributes and Kp index: We further include extra attributes for accuracy assessment: the total number of satellite points included in the interpolation, the average and minimum distance values and finally the average Kp index which helps to identify when there is high magnetic disturbance at the location and time of each GPS point (German Research Centre for Geosciences 2021).

Step No 5. Calculate the additional geomagnetic components: In the last step, the method calculates additional geomagnetic components such as the magnetic intensity F, Horizontal component H, Declination D, and Inclination I. The method creates a Python pandas dataframe that integrates the original attributes from the given trajectory with the interpolated geomagnetic components creating an new annotated table that can be exported or use it to plot it as map using additional libraries like geopandas or create charts to explore the geomagnetic variations along the GPS trajectory directly in the notebook.

3. Discussion and Future Work

MagGeo is a tool that, for the first time, provides researchers with the opportunity to explore the potential animal response to the short-term geomagnetic variations with real geomagnetic data. This is exciting as it opens new lines of analysis where animal movement researchers can now explore large multi-species tracking data towards a better understanding on how the geomagnetic conditions might affect the migratory patterns. As suggested lines of improvement, initially, this tool can be integrated in other popular tools like EnvData from Movebank (Dodge *et al.* 2013:1–3) where researchers can annotate environmental data from reliable satellite sources with the animal trajectories. The interface and platform where MagGeo is deployed (Jupiter Notebook) can be translated into a more familiar environment in movement ecology, i.e. R. Finally, the addition of new methods of interpolations can help to improve the MagGeo's potential to reflect changes on the geomagnetic field across both time and space.

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