

Drone-Based Magnetic Survey: Testing a New Approach for Archaeological Prospection

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Abstract

In recent times, drones equipped with a variety of sensors, such as multispectral, thermal, and LiDAR, have been increasingly used in various archaeological tasks. There is also a growing interest in using geophysical sensors, like magnetometry (MAG), on Unmanned Aerial Vehicles (UAVs). One of the key challenges is selecting the most suitable and effective systems for archaeological purposes. Succinctly, this paper aims to assess the inner workflow established of Drone-based MAG system and briefly highlight its advantages and limitations in the archaeology field. Instead of discussing specific market-available systems, this essay provides a comprehensive overview of Drone-based MAG applications.

CCS Concepts

- **Drone-Based magnetic survey** → workflow, challenges.
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1. Introduction

In recent decades, various drone-based systems equipped with several types of sensors, including LiDAR, RGB, multispectral and thermal cameras have been tested across numerous archaeological applications. These systems have been utilized for three-dimensional (3D) documentation of archaeological excavations, 3D monitoring of monuments, surveying of archaeological sites, landscapes, and woodland areas, as well as for conducting assessments in the realm of ‘preventive’ archaeology (Cam17; Cic24; CMR*2025). Recently, there has been increasing interest in using geophysical sensors, such as magnetometry and ground-penetrating radar mounted on drones. Some European archaeological projects (GRM2021; SLS*2022) have begun testing drone-based magnetometer systems, emphasizing high precision and accuracy in surveying complex sites and territories.

2. Main objectives

The primary aim is to establish a workflow for utilizing drone-based magnetometers in archaeological fieldwork.

This methodological research aims to develop a first draft of an operational protocol for non-invasive investigations for studying archaeological contexts by geophysical approach. The main objective is to collect magnetic data to streamline traditional archaeological prospections in landscape archaeology in order to offer a preliminary magnetic map that can be followed up with ground-based magnetic surveys for further insights. Therefore, a drone-based magnetometer will be able to reduce surveying time and increase the area surveyed in hectares. The proof of this was already verified through previous testing in the German region (SBS2020; SLS*2022). When acquiring magnetic data with drone-borne magnetometers over extensive areas, it is essential to evaluate the capabilities of the defined operational workflow and processing chain. Integrating drones with magnetometers offers a highly promising approach for surveying and mapping archaeological sites that would otherwise be inaccessible due to difficult terrain, both at local and large scales.

3. Advantages and limitations of drone-based geophysics

The transition from terrestrial geophysical data acquisition systems to aerial platforms such as drones involves numerous differences. The most evident one is the absence of direct contact with the ground, which offers significant new opportunities, primarily by

freeing detection opportunities from both land use and ground conditions. Aerial platforms allow, for instance, the execution of measurements in tilled grounds, sown fields, ongoing crops, as well as extremely stony areas or inaccessible scrublands to traditional terrestrial systems. It is also possible to conduct surveys in conditions of heavily saturated or flooded soil, snowy environments, and so on. Weather and lighting conditions become irrelevant as both the sensors and the latest generation drones are all-weather. Another point of interest is the drones' suitability for automation. It is now quite common to conduct drone surveys by planning the area of interest and executing the flight in fully automated mode. The prospects of further short- and medium-term developments open completely new scenarios even in the field of geophysical surveying, envisioning scenarios for activities that allow fully automated multiple systems to be used simultaneously, maximizing productivity by surveying overnight. Lastly, a significant aspect is the speed of detection, which, thanks to all the listed features (all-weather, automation, 24/7 surveying, etc.), could increase exponentially.

The main limitations consist of the distance of the magnetic system from the ground and the electromagnetic interference generated by the drones. Although it is currently possible to significantly reduce the distance from the ground, it remains difficult to operate much below one meter above the surface with ongoing crops. In contrast, whether the ground is totally free by crops, such as a plugging or freshly sown ground and in the perfect weather conditions, the sensor can be lowered to the maximum possible, approximately around 40/50cm AGL (Above Ground Level) (Figure 1). Excessive distance significantly affects the acquisition of magnetic measurements. In the case of magnetic surveys, the situation is further complicated by the magnetic interferences generated by the drones. All this effectively results in a reduced capacity to detect archaeological targets, particularly those that are more ephemeral in terms of magnetic field variation and radar echo reflection. As already indicated by recent scientific publications (e.g., SKL*2023 KGA*2023), several significant issues related to the drone-based magnetometer system, especially in the Sensys R4 MagDrone, have been identified, stemming from factors intrinsic to the sensor-platform combination. The R4 magnetometer, consisting of five three-axis fluxgate magnetometers mounted horizontally beneath the drone, such as the DJI Matrice 350 RTK (Figure 1), is not the most optimal solution due to strong electromagnetic interference caused by the 100+ KHz currents (high-frequencies) generated by the drone's propeller motors and platform. Moreover, the low-frequency static magnetic field produced by the drone's power-current flow poses a major challenge, which can be mitigated by positioning the measurement sensors as far as possible from the drone body. A general compensation procedure has been successfully defined elsewhere (KGA*2023).



Figure 1. R4 MagDrone system testing. Possibility of access to cultivated or private lands. On the right, representation of the arrangement of the five sensors inside the horizontal magnetic bar, placed below the drone.

It was observed that sensors 1 and 5, which lie at the ends of the horizontal magnetometer array, recorded the lowest noise levels, whereas sensor 3 — located directly beneath the drone — exhibited the highest noise. In the R4 mag-drone system, all five magnetometers travel along the same survey line, and the drone translates without changing its heading. This configuration minimizes heading-related variations, so the inter-sensor offsets — the constant differences in magnetic readings between each pair of sensors (\pm nT) — can be treated, in first approximation, as time-invariant biases. Estimating these constant offsets and removing them during post-processing is therefore the central objective of this work to improve the reading of magnetic data (Figure 2).

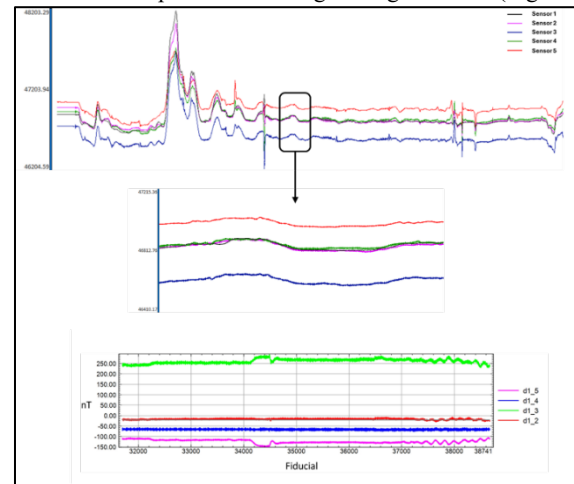


Figure 2. It shows the representation of a different offsets between five sensors highlighted in the high-altitude flight profile.

As shown in Figure 3, we defined a workflow structured in three levels, from data acquisition to data interpretation. First, the areas to be investigated are defined in a GIS environment (QGIS), and the vector layers are imported into UgCS software

(sphengineering.com) for planning the flights (first level workflow). Here we specify all mission parameters — flight lines, altitudes, and RTK-GPS settings — so that both calibration and survey flights precisely cover the target polygons. As previously mentioned, the offset compensation represents the main challenge for the application of the R4 mag-drone system, especially in the archaeological field. For this reason, magnetic data is acquired in two sequential flights. The first flight in high-altitude pass at 100–120 m AGL measures the Earth’s relatively uniform magnetic field, isolating each of the drone’s five sensors’ stable offsets. At this elevation, only broad-scale geological magnetic anomalies remain — wavelengths of tens of meters — so the parallel time series recorded by each sensor reflect essentially constant biases. The drone’s level flight and steady attitude make short-term deviations from motor-current transients or attitude changes insignificant. We calculate each sensor’s meaning offset based on this dataset. The ground-based flight (the second flight) using the R4 MagDrone system, is conducted based on a specific measuring height and speed. The flight altitude is instrumental in determining the data acquisition, because it is necessary to define the correct distance between the magnetometer and the ground surface. We conducted the ground-based survey at ≤ 1 m AGL to capture the rapidly decaying archaeological signal. A radar altimeter or LiDAR-based Terrain Following System keeps the magnetometers at a consistent height above uneven terrain, while a differential GPS in RTK rover mode provides centimetric georeferencing. Flying at approximately 2 m/s minimizes oscillations and forward tilt, thus reducing lag effects and noise in the magnetometer readings. The second level is based on the pre-processed magnetic data in MagDrone Data Tool Software (MDDT, <https://sensysmagnetometer.com>), downsampled from 200 Hz to 25 Hz (exported in ASCII format). This reduction is essential for attenuating the high-frequency noise produced by the drone’s propeller motors and platform.

The third level workflow involves the actual processing of magnetic data in a software, where it is possible to remove the offset of the five magnetometer sensors, interpreted as a ‘trend’ between all sensors in high-altitude flight data. Since the relative orientations of the five tri-axial sensors are unknown, we compute the magnetic field magnitude from their three-component measurements for each sensor. We subtract each sensor’s high-altitude offset from its corresponding ground-flight time series. An additional computational step involves refining the removal of inter-sensor offsets using a numerical filter specifically designed for this case.

4. Spatial Low-Pass Filtering of Orthogonal Profiles

In our processing workflow, the raw magnetometer readings are first resampled along profiles oriented orthogonally to the drone’s flight direction (cross-track transect). As each profile crosses from one sensor footprint to the next, the constant inter-sensor biases produce abrupt jumps (high-spatial-frequency oscillations) (Figure 4 above). To remove these offset-induced artifacts, each orthogonal profile $V[i]$ is passed through a finite-impulse-response low-pass filter defined by a windowed-sinc kernel $h[k]$ of length $2L + 1$.

Given the cutoff wavelength λ (in samples):

$$L = \text{floor}(\lambda_c) , \quad k = -L, \dots, 0, \dots, +L$$

λ_c denotes the cutoff wavelength in units of samples, which determines the spatial extent over which low-frequency variations are preserved. The floor operator rounds λ_c down to the nearest integer, yielding the half-length L of the filter kernel.

Thus, if $\lambda_c=20.7$ then $L = \text{floor}(20.7) = 20$. The index k then spans from $-L$ to L , so that the kernel $h[k]$ comprises $2L + 1$ coefficients symmetrically centered around zero.

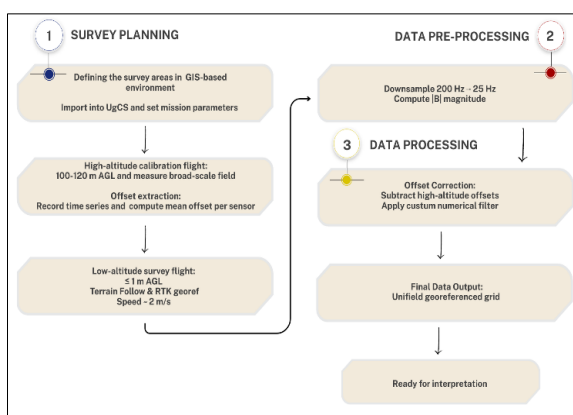


Figure 3. The workflow is proposed and structured in three connected levels, from data acquisition to data interpretation.

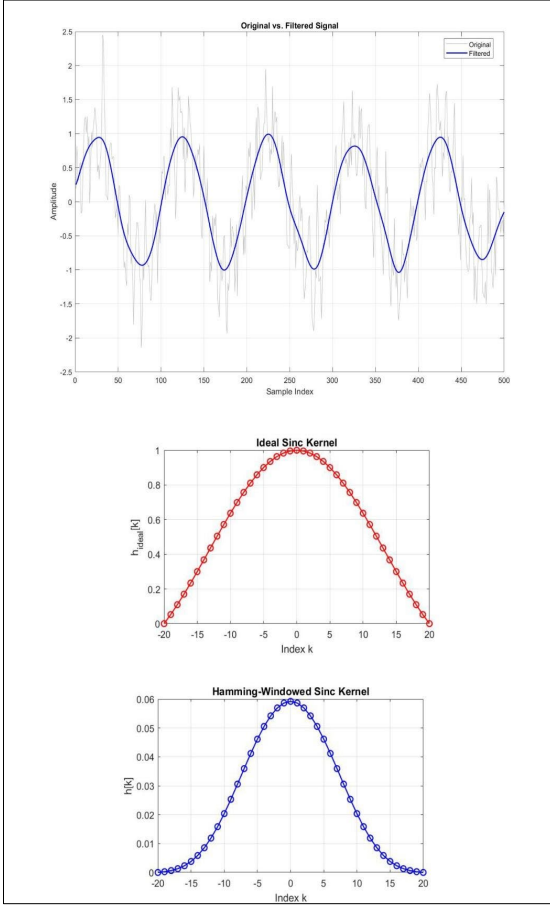


Figure 4. Example of a function consisting of a low-frequency signal modulated by a high-frequency component. The spatial-domain convolution filter is able to correctly remove the high-frequency content (filtered signal). Ideal sinc kernel (red circles) and sinc kernel with a Hamming window (blue circles) are shown.

The ideal impulse response is the sinc function:

$$h_{ideal}[k] = \text{sinc}\left(\frac{k}{\lambda_c}\right)$$

which is then tapered with a smooth Hamming window $w[k]$:

$$h[k] = h_{ideal}[k] \cdot w[k]$$

Normalization for unity gain:

$$\sum_{k=-L}^{+L} h[k] = 1$$

The filtered profile is then computed by discrete convolution:

$$F[i] = \sum_{k=-L}^{+L} h[k] \cdot V[i - k]$$

Spectral components above the cutoff frequency $f_c = \frac{1}{\lambda_c}$ (the offset-related oscillations) are thus attenuated, while genuine low-frequency magnetic anomalies are preserved. The smoothed values F can then be interpolated back onto the original survey grid to produce a continuous, low-noise anomaly map free of systematic inter-sensor offsets.

5. Conclusions

The current work has shown that experienced data processing workflow can refine magnetic values to minimize offsets between sensors, eliminating the offset is challenging. The offset-related correction between sensors is essential to improve the reading of magnetic data, as each sensor measures nT values of different points, producing sampling profiles with non-constant values. However, the integration of magnetometers on close-range platforms such as drones is opening new horizons in archaeology, allowing researchers to conduct non-invasive site investigations. These systems excel at accessing difficult terrain, accelerating data collection, and delivering precise survey results.

At present, the main aim of drone-based magnetometry is to distinguish areas with buried anthropic deposits from those without. The system is most effective for locating large features and structures with moderate to strong magnetic signatures. While weaker anomalies may go undetected, this approach provides rapid, broad-area magnetic maps that guide more detailed ground-based magnetometry. Importantly, a lack of anomalies in drone maps does not guarantee the absence of buried remains; factors like local geological background, sensor resolution, flight altitude, and electromagnetic interference can play a fundamental role to mask weaker archaeological signals. Therefore, the research team composed of the University of Salento, INGV, and University of Siena, are investigating methods to separate the drone's own magnetic influence from true archaeological signals. The next step will be integrating data from a ground-based R4 magnetometer, which will clarify the drone's magnetic footprint and help filter out electromagnetic noise.

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