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DRONE-BORNE MAGNETIC GRADIOMETRY IN ARCHAEOLOGICAL APPLICATIONS: A METAPONTO CASE-STUDY

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Introduction

Applied geophysics offers non-invasive techniques to uncover and characterize buried structures or characterize the type and quality of materials in archaeology. Among the various geophysical methods, the magnetic method stands out due to its effectiveness, speed, cost-efficiency, and non-invasive nature. This method leverages the magnetic susceptibility contrasts between archaeological features and the surrounding soils, making it particularly useful for detecting and mapping subsurface remains[1].

The magnetic method is highly sensitive to both natural sources, such as soils and rocks, and man-made objects, including ditches, storage pits, foundations, and walls. This sensitivity allows geophysicists to identify significant anomalies that indicate the presence of archaeological targets. The method's ability to produce high-resolution data quickly and efficiently makes it a preferred choice for large-scale surveys.

Magnetic anomalies generated by archaeological targets are typically weak, dispersed over small areas, and often interfere with each other. Therefore, high-resolution magnetic data, collected with closely spaced survey lines near the ground, are essential for their identification. The survey area must be large enough to provide informative anomalies, especially for regular and elongated shapes of buried structures like buildings or roads.

One of the most advantageous applications of the magnetic method in archaeology is the use of gradiometric surveys. Gradiometric surveys involve measuring the magnetic gradient, which enhances the detection of shallow sources and improves the resolution of the data[2]. This approach is particularly beneficial in archaeological contexts where the anomalies are often weak and spread over small areas. By using a pair of sensors to measure the magnetic field at different heights, gradiometric

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1. Bianco *et al*. 2024; Schmidt - Becken - Schmalzl 2020.

2. Slack - Lynch - Langan 1967.

surveys can effectively filter out temporal variations and regional magnetic fields, focusing on the anomalies generated by archaeological features. Often, the two sensors are arranged in a vertical direction and spaced at a fixed distance, called the 'baseline'. The choice of the length should be smaller than the distance between the sensor closer to the ground and the source depth. Therefore, depending on several conditions, the baseline for hand-held magnetometers ranges between a minimum of 0.25 m and a maximum of 1 m.

Recently, applied geophysics have further revolutionized methods of data acquisitions through the adoption of Unmanned Aircraft Vehicles (UAVs) equipped with new miniaturized magnetometers. UAV-based magnetic surveys can cover extensive areas at low altitudes, providing high-resolution datasets that are crucial for identifying subtle archaeological features. This technology is especially useful in challenging environments where ground-based surveys are impractical[3].

We conducted a UAV magnetic investigation in the archaeological site of Metaponto, arranging the magnetic sensors of the Geometrics Micro-Fabricated Atomic Magnetometer (MFAM) as a gradiometer. Then, aerial data was compared with a ground dataset used to validate the quality of the measurements collected with the drone.

The Test Site

Both ground and UAV surveys were conducted in the archaeological site of the Tavole Palatine at Metaponto, Basilicata, southern Italy. The site lies on a low hill rising above the nearby Bradano river, which marked the boundary between Metaponto and Taranto during antiquity and which is closely paralleled by the modern border between the regions of Basilicata and Puglia. The hill was first occupied during the Neolithic period, as attested by a group of axes and numerous ceramic sherds from historic excavations[4]. This was followed by a caesura of several millennia, with the earliest Greek occupation attested by fragments of Corinthian pottery of the 7th century BCE, to be connected with the foundation of the colony of Metaponto at the end of that century. Votive materials demonstrate ritual practice within the sanctuary well before the construction of a peripteral Doric temple during the last quarter of the 6th century BCE[5]. The sanctuary and temple were dedicated to Hera, as evidenced by fragments of a marble basin with an inscription naming it property of the goddess[6].

This Late Archaic temple was constructed almost entirely of a calcareous stone (sometimes called by the non-geologically specific terms *tufo calcareo* or *mazzaro*), which Cancellieri and Lazzarini have identified as a fine-grained yellow calcarenite (more properly termed a grainstone), while in the crepidoma occur rare blocks of a

3. Cunningham *et al*. 2018; Parshin *et al*. 2018; Walter - Braun - Fotopoulos 2020; Accomando *et al*. 2023; Kim *et al*. 2021 ; Mu *et al*. 2020 ; Nikulin - de Smet 2019 ; de Smet *et al*. 2021.

4. Lo Porto 1981, pp. 25-26.

5. Mertens 2006, pp. 216-219; Lippolis - Livadiotti - Rocco 2007, p. 793.

6. Galli 1928, p. 76; Lo Porto 1981, p. 27, n. 21.

cemented conglomerate of fluvial origin[7]. This conglomerate, the use of which is probably to be connected to ancient repairs, outcrops in at least two locations in the Metapontine chora, at Castelluccio and near Casa S. Biagio, and hence can be considered a local stone. The yellow calcarenite, on the other hand, is absent from the immediate vicinity of Metaponto; the geoarchaeological analyses of Cancellieri and Lazzarini indicate the territory of Taranto as the likely source of this stone, identified as pertaining to two formations, the Calcareniti di Gravina and Calcareniti di Monte Castiglione, without however being able to pinpoint any single quarry of origin. Any subsurface architecture at the site is likely to be composed of similar materials.

(DPD)

Measurements and Survey Design

The GEOMETRICS Micro-Fabricated Atomic Magnetometer (MFAM) in the "Development kit" version, a high-resolution Cs-vapor magnetometer, was utilized for both ground and UAV surveys. This magnetometer is well-known for UAV applications due to its high sensitivity, light weight, and compact size. Its most notable feature is the high sampling frequency of 1000 Hz, which effectively detects the most prominent noise components generated by the drone and power lines. The magnetometer was placed in the same custom bird previously described by Accomando et al. 2021[8], a light, aerodynamic and nonmagnetic polystyrene bird with a thin and rigid base, modified by adding a fin-shaped polystyrene frame that maintains, between the MFAM sensors, a baseline distance of 0.25 m to measure the total field vertical gradient (fig. 1a).

The selection of the survey area for the UAV magnetic survey was influenced by obstacles such as tall trees and a hedge surrounding part of the site. While these obstacles can typically be bypassed by flying drones overhead, we opted to fly as close to the ground as possible to ensure data quality. In earlier studies, we demonstrated that for surveys over intense magnetic anomalies, a practical and safe method to carry the magnetometer is to attach it rigidly to the drone's landing gear, just 0.50 m from the engines. However, for this study, given the low-amplitude magnetic fields expected from the archaeological targets, we chose to suspend the magnetometer 3 m below the platform (fig. 1b), which is the standard distance to minimize magnetic and electromagnetic interference from the drone and its rotors. Consequently, the UAV flight altitude was 7 m, covering an area of 35 m x 10 m (fig. 2). With the magnetometer attached to the UAV by four 3 m-long ropes, the magnetic sensors were positioned 4 m above ground level. The magnetometer's 1000 Hz sampling rate and the flight speed of 2 m/s allowed for magnetic data collection every 2 mm along the 11 survey lines flown in a roughly North-South direction. The distance between survey lines was 1 m.

7. Cancellieri - Lazzarini 2019, employing thin-section, XRF, ICP-AES, and mass spectroscopy.

8. Accomando *et al*. 2021.

Fig. 1. MFAM configurations used for the surveys. a) Geometrics MFAM "Development kit" arrangement inside the prototype bird with the additional frame which allows distancing of the sensors; b) UAV flight configuration.

We also conducted a ground survey with the MFAM using the gradiometric configuration in the same area, though slightly more extended in the North-South direction compared to the UAV survey. The sensors were carried approximately 0.30 m above the ground. The acquisition speed and measurement spacing along the survey lines were similar to those used in the UAV surveys. The line spacing was 0.50 m, and the survey lines were oriented similarly to the UAV survey.

In windy conditions (as during the survey), suspending the magnetometer with 3 m-long ropes can cause unwanted sensor oscillations[9], potentially compromising both flight stability and data quality. To address these issues, we enhanced the flight configuration stability by adding a wooden support that widened both the suspended magnetometer support base and the drone's landing gear (fig. 1b).

The magnetic ground survey lasted approximately 45 min while the flight lasted approximately 7 min. During the time interval in which the drone-borne ground magnetic surveys were completed, the total magnetic field was monitored at a point in the same survey area. The total field variations were negligible, so that no temporal correction was applied to the three datasets.

9. Accomando *et al*. 2021; Walter - Braun - Fotopoulos 2019.

Fig. 2. Aerial photo of the Greek temple of the archaeological site of Metaponto-Tavole Palatine with its colonnades; the yellow and red box indicate, respectively, the areas covered by ground and UAV datasets.

Results

Both the total magnetic field and its vertical gradient are not immediately suitable for analysis since raw maps are usually characterized by errors of various types. Therefore, a good data processing to remove or minimize errors is essential for correct interpretation, especially in the case of archaeological remains that produce very weak signals, which often need to be enhanced.

Below, we present the complete workflow used for the magnetic dataset, discussing the typical features of noise which occur during a magnetic survey with a particular focus on the UAV data.

Fig. 3 shows a map of the drone-borne Total-Field Anomaly (TFA) measured at both magnetometer sensors and the map of the relative vertical gradient. The measurements are unfiltered. The sensor closer to the ground (s2) was at 4 m elevation and the other one (s1) was 0.25 m above.

The TFA maps, displayed in fig. 3, present a typical noise that occurs when magnetic measurements are taken in a bi-directional mode. These different amplitudes (resulting in maps with characteristic 'striping') can be associated with a strong heading error: the data acquired from South to North have a lower average value and noise amplitude than those acquired from North to South[10]. Its amplitude depends on

10. Scollar *et al*. 1990.

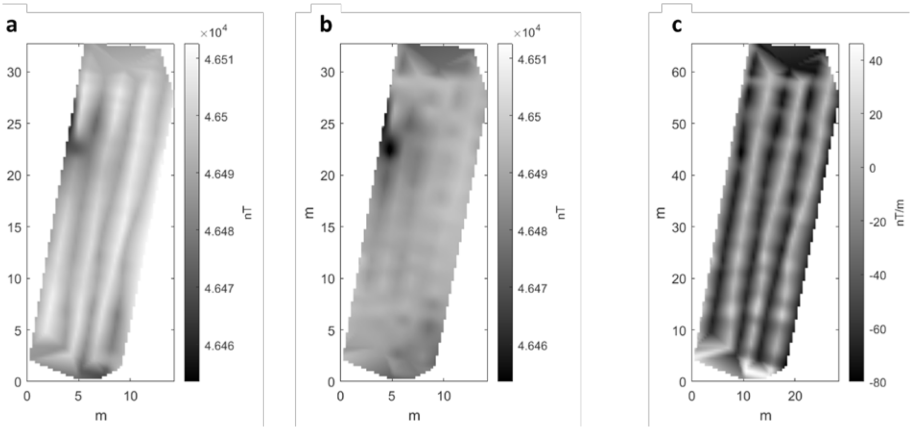

Fig. 3. Un-filtered Total-Field Anomaly (TFA) maps. a) TFA map obtained from sensor 1; b) TFA map obtained from sensor 2; c) Vertical gradient map.

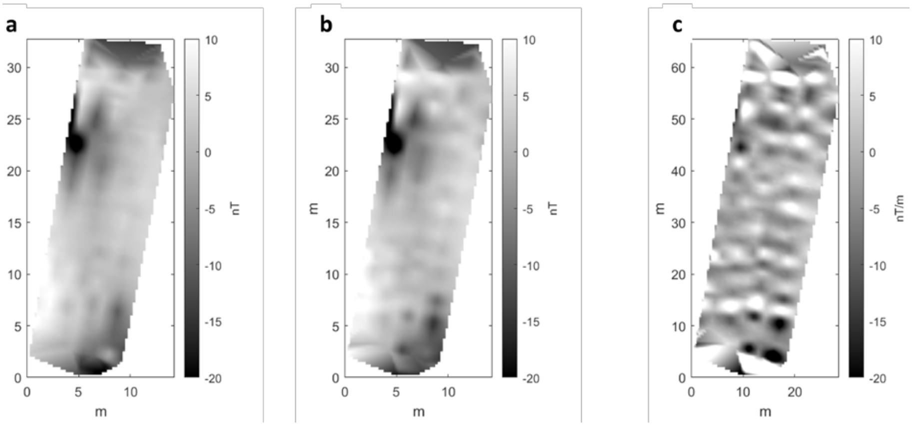

Fig. 4. Total-Field Anomaly (TFA) maps, after removal of heading error.
a) TFA map obtained from sensor 1; b) TFA map obtained from sensor 2; c) Vertical gradient map.

the fact that the sensors are placed in the volume with the strong magnetic effect of the UAV. In fact, the drone has its own magnetic effect, and the position of the magnetometer sensors with respect to this UAV-related magnetic effect may change with the flight direction, altering the average value and the noise amplitude of the recorded data from line to line. This effect is particularly noticeable in the map corresponding to the sensor closest to the drone (fig. 3a) and significantly impacts the computation of the vertical gradient (fig. 3c). However, just 0.25 m lower, the heading error is still present but less pronounced (fig. 3b).

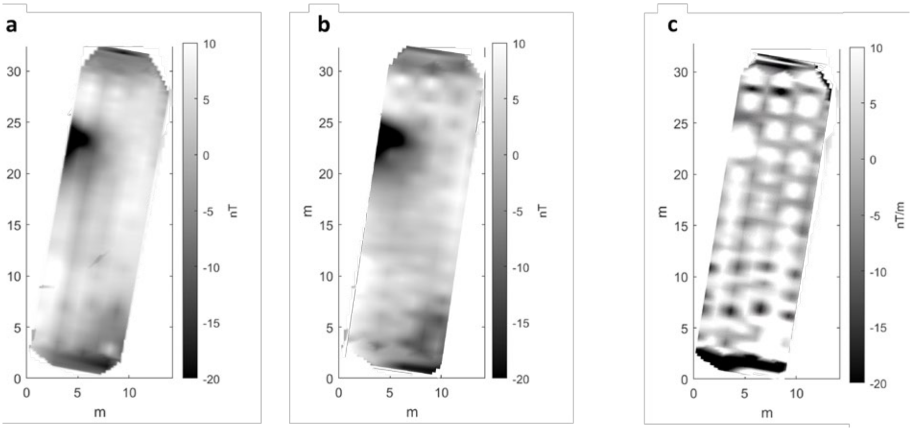

Fig. 5. Total-Field Anomaly (TFA) maps, after removal of zig-zag effect. a) TFA map obtained from sensor 1; b) TFA map obtained from sensor 2; c) Vertical gradient map.

We corrected this error by equalizing the data acquired along each line of the measured field to the same mean value[11]. The result is shown in fig. 4.

Moreover, a second feature of noise, typically due to a system in flight, is the oscillation of the suspended magnetometer, especially in the presence of a strong wind during the acquisition. These effects are particularly evident in the map of the sensor 2 (fig. 4b) and strongly influences the computed vertical gradient (fig. 4c), which shows an alternation of magnetic highs and lows with a wavelength of about 2.5 m. Another effect refers to a pattern of oscillations or irregularities that can appear in the recorded magnetic field measurements known as the zig-zag effect. It is often caused by inconsistencies in the movement of the sensor, such as those induced by the UAV's flight path or environmental factors like wind. These oscillations can introduce noise and distortions in the data, making it challenging to interpret the magnetic anomalies accurately. Consequently, to mitigate this noise, we used several techniques (suggested by Eder-Hinterleitner et al. 1996 and Ciminale and Loddo 2001[12]) that smooth out these irregularities and enhance the quality of the magnetic data, as shown in fig. 5.

However, the resulted TFA maps still present linear artifacts (fig. 5a,b), and the calculated vertical gradient is affected by strong oscillations represented by the alternation of maximum and minimum (fig. 5c). In this case, to mitigate the striped feature of noise in specific directions, we used the discrete wavelet transform (DWT[13]), while a low-pass filter could be useful to remove the high wavenumber noise, in part associated with the oscillations of the suspended system.

11. Ciminale - Loddo 2001.

12. Eder – Hinterleitner - Neubauer - Melichar 1996; Ciminale - Loddo 2001.

13. Fedi - Quarta 1998; Fedi - Florio 2003.

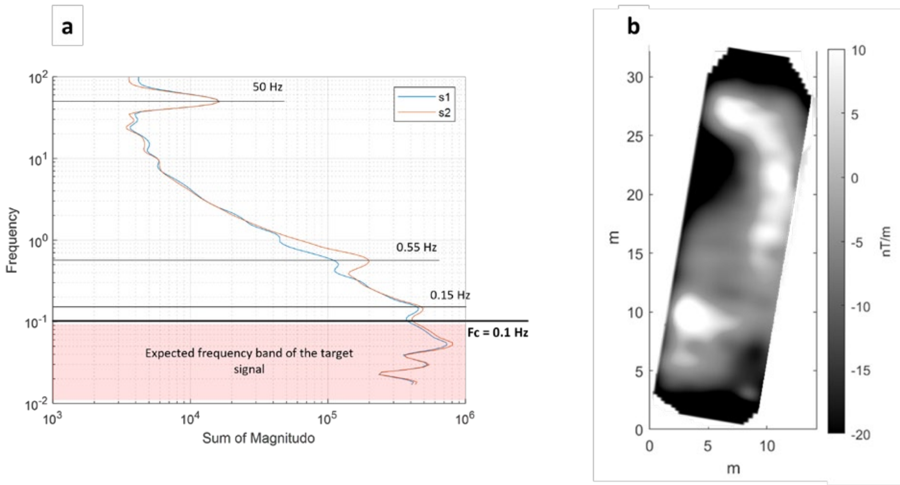

Fig. 6. a) Power spectrum of data. The blue and orange lines are referred to, respectively, the first and second sensor signals. The red lines indicate the mean noise peaks: 1) 50 Hz relative to the power lines; 2) 0.55 Hz and 0.15 Hz are interpreted as generated by the oscillations of the system; b) Filtered vertical gradient maps of the UAV dataset.

Thanks to the continuous wavelet transform (CWT), as shown in fig. 6a, we studied the spectral content of the acquired magnetic signal. The prominent spectral peak at 50 Hz is due to the sum of two main contributions: 1) the alternate fields generated by the AC power lines present in the area; 2) to a much lesser extent, the magnetic and electromagnetic fields generated by the UAV platform[14]. In fact, this peak presents the same amplitude for both MFAM sensors. Moreover, 0.55 Hz and 0.15 Hz are the peaks associated with the oscillations of the system in flight. Finally, we are able to determine the frequency band associated with the target signal[15] that in this case does not spectrally overlap with the swinging spectral contents. So, we used 0.1 Hz as cut-off frequency for a time-domain Hanning-window low-pass filter to preserve the useful signal at lower frequencies, removing all the noise effects. The vertical gradient obtained from both the DWT and low-pass filter (cut-off frequency of 0.1 Hz) is shown in fig. 6b.

The vertical gradient map displays an amplitude variation of about 30 nT, ranging from about -20 to 10 nT. The clearest feature is the extended magnetic high with an amplitude of about 5-8 nT/m, trending NE-SW, which crosses the entire area for some tens of meters.

The processing of the ground datasets required fewer steps than the UAV workflow. Here, for example, both the oscillation effects and the heading error features

14. Walter - Braun - Fotopoulos 2021.

15. Accomando *et al*. 2021.

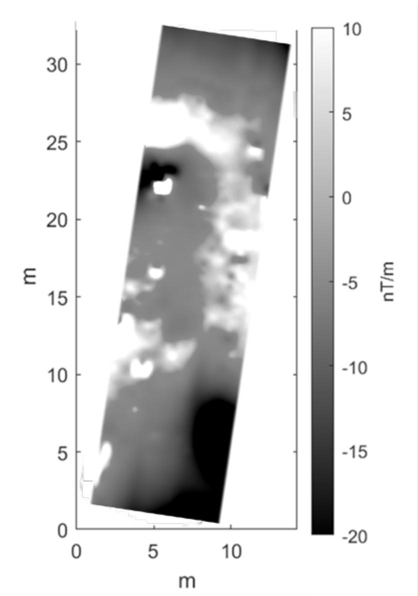

Fig. 7. Filtered vertical gradient maps of the ground dataset.

were weaker. Therefore, a low-pass filter to remove the contributions at high frequencies due to the power lines and a light DWT to compensate several striped anomalies were enough to ensure a good result. The filtered vertical gradient map (fig. 7) obtained from the ground survey shows a main magnetic feature similar to that detected in the UAV one. However, as expected, in the ground case, the shape of the magnetic features is better defined since the magnetic sensors were transported very close to the ground. Overall, the results obtained from ground and UAV surveys are very similar.

Discussion and Conclusion

The development of drones and their use in magnetic surveys has revolutionized the strategies of acquisitions, offering a faster and more cost-effective option compared to traditional methods as well as the only one solution of access to remote and challenging areas.

Despite the fact that archaeological targets are usually weak, this study tries to demonstrate the reliability of drone magnetic survey even for archaeological applications. To improve sensitivity and resolution, we implemented a vertical gradiometer to be used both for ground and UAV survey.

However, the successful implementation of drone-based magnetic measurements hinges on the correct and versatile processing of the collected data. Drones induce several disturbances, such as electromagnetic interference and oscillations effects which can affect the accuracy of the measurements. Therefore, it is crucial to employ data processing techniques to filter out these disturbances and ensure the reliability of the results.

In this study, we verify the quality of UAV data by comparing the drone dataset with ground measurements. The data processing workflow for drone-acquired magnetic data often necessitates additional steps compared to traditional methods. These steps include addressing significant heading-error issues, managing the oscillations of suspended sensors, and correcting for drone-induced magnetic fields. However, it is crucial to consider common noise features and implement practical solutions to mitigate them. By doing so, we can reduce the need for strong filters during data processing. For example, maintaining one constant heading throughout the entire survey, without performing the 180° turn at the end of each line, ensures the minimization of the heading error. The best way to prevent the heading error is to not acquire the data in a bi-directional mode, but this would cause a slowdown in the data acquisition both for ground and UAV surveys. Therefore, it could happen that some directional noise still effects the result, and, in this case, it would be necessary to use a directional filtering after the removal from each profile of field mean value. Another important suggestion is that most geophysical methods, like the magnetic one, are extremely sensitive to the altitude above the investigation target, so the use of a DEM or a laser/radar altimeter, which allows following the exact topography of the terrain, guarantees the requested resolution for magnetic investigations. Due to the archaeological context and the expected weak magnetic anomalies, we preferred to keep the magnetometer sensors outside the region of the highest drone interference by suspending the MFAM at 3 m from the mobile platform. However, this strategy does not ensure a great stability of the system during the flight. To mitigate this issue, we modified the flight configuration by using wooden supports that widens to 90 cm the distance between the anchor points at both the suspended magnetometer support base and drone landing gear (fig. 2b). Often, this represents a good choice but in other cases this improvement could be insufficient to guarantee a clean signal, and the use of filters is needed.

For both the flight and ground configuration, we used a baseline between the MFAM sensors of 0.25 m. This solution, maybe because the target investigated is very shallow, worked well in our case. However, the sensor distance should be increased in the case of deep targets or for UAV magnetic surveys at higher altitude.

UAV and ground vertical gradient data acquired seems to be very similar. Both highlight an elongated NE-SW trending magnetic high, probably due to a different quality of the soil, perhaps caused by a ditch, successively re-filled. This warrants further geophysical surveys that will be planned to cover the entire area of the archaeological site.

In conclusion, drones represent a transformative tool in magnetic measurements and have a role also in archaeological investigations. By addressing the challenges related to data processing, researchers can leverage the full potential of UAVs, obtaining high-resolution results that are essential for the entire field of interest of the magnetic method. As technology continues to advance, the role of drones in magnetic surveys is set to expand, driving further innovations in the field.

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