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# An Integrated Approach for Ground and Drone-Borne Magnetic Surveys and their Interpretation in Archaeological Prospection

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## Highlights:

- Availability of fast and precise ground and drone-borne magnetic surveys.
- Extraction of information on the sources through potential field transforms.

**Keywords:** magnetometry, potential field transforms, drone, Fluxgate, inversion.

Magnetic surveying is nowadays a popular tool for the detection and mapping of archaeological remains (e.g. Gaffney, 2008; Fassbinder, 2017). The EAC Guidelines for the use of geophysics in archaeology (Schmidt *et al.*, 2015) give an overview of the practical uses of magnetic methods. Magnetometry is often the faster and cheaper of the geophysical methods, and is frequently used for prospecting before or in complement of other geophysical methods and archaeological excavations. Most of the time, measurements are made with fluxgate vertical-component gradiometers, which have the great advantage of being light, robust, relatively cheap, mostly unaffected by time-induced variations (i.e. noise), and sensitive to very near-surface heterogeneities (i.e. the first meter). Less commonly, scalar magnetometers can be used (based on alkali vapor optically-pumped or proton precession principles). They are heavier, more fragile and more expensive than fluxgate magnetometers. They are impacted by time-induced variations but are more sensitive to deeper sources and smaller magnetization contrasts than gradiometers. Two scalar magnetometers can be placed vertically to build a scalar gradiometer. An instrument of this kind has an output quite similar to the one of fluxgate gradiometers. Magnetic compensation (i.e. cor-

rection of the effect of the magnetization of the equipment on the data) is not performed with the described instruments. Instead, the sensors are deported as far as possible of the magnetized components of the equipment. Finally, the interpretation is usually made directly on maps of the pseudo-vertical gradient. The use of quantitative methods such as potential field transforms, direct modeling or inverse problem to obtain additional information on the sources is not very common. This is possibly due to the fact that the output of the device is not strictly the gradient (a flux), but an approximation (difference between two sensors). Such approximation is usually considered accurate enough for producing a pseudo-gradient map, but can be hazardous when computing the data in the spectral domain (hence using potential field transforms). Magnetic surveys are also quite common in the field of resources exploration and geological studies, usually using scalar magnetometers mounted on aircraft (Nabighian *et al.*, 2005). A magnetic compensation of the equipment is performed with heavy active compensation systems and the time-induced variations are corrected post-flight. The interpretation of the data is usually performed using tools from potential field theory to gain information on the sources (precise horizontal posi-

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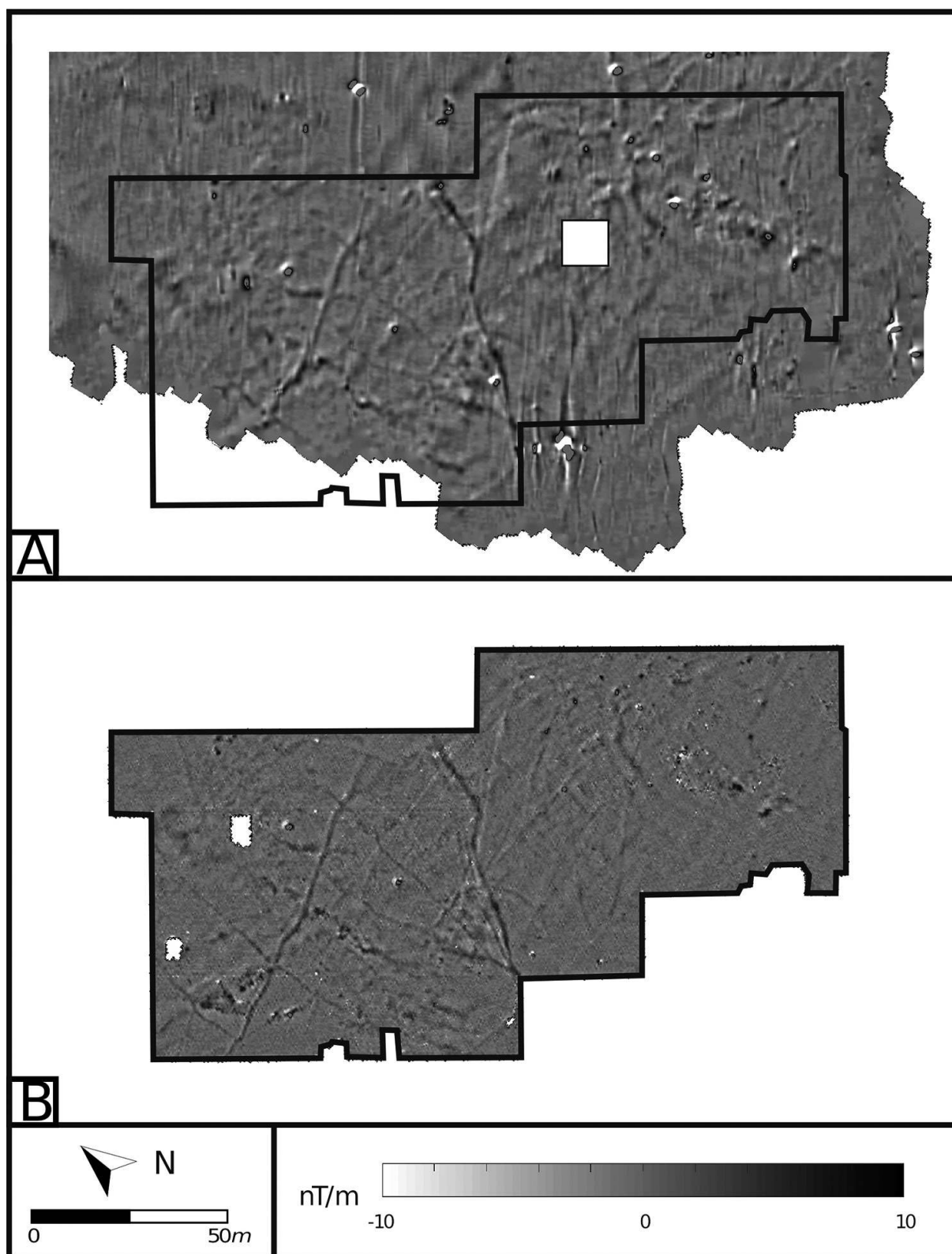


Figure 1. Comparison between: (A) vertical gradient computed from TMI data acquired 1 m above the ground; (B) vertical gradient measured 0.3 m above the ground (Gavazzi *et al.*, 2017).

tion, depth, magnetization). Here we propose an innovative approach aiming to integrate different aspects of the two communities, in order to build new tools to study archaeological objects, from the excavation to the regional scale. Our approach is based on the use of three-component fluxgate magnetometers. They are based on the same physical principle as the fluxgate gradiometer, i.e. the measurement of a directional component of the magnetic field. Instead of the measurement of a difference of vertical components between two points (the concept of the gradiometer), three orthogonal components are measured simultaneously at the same point. The aim is to compute the magnetic intensity (i.e. like the output of scalar magnetometers) in order to be able to use the potential field theory and perform a passive magnetic compensation of the equipment. This passive compensation ability from a simple procedure in the field was published in

2007 for the detection of unexploded ordnance with a precision of two nT (Munsch *et al.*, 2007). Mono- and multi-magnetometer systems have been developed for ground, drone and aircraft surveys (Gavazzi *et al.*, 2016). Such devices have been used in ground surveys for archaeological prospection with increased resolution (0.3 nT), in large scale surveys over dozens of hectares (e.g. Gavazzi *et al.*, 2017) to high-resolution surveys of subtle structures like post holes (e.g. Wassong & Gavazzi, 2020). Overall, the use of this kind of equipment with potential field interpretative tools showed a high versatility for archaeological, environmental and geological applications at different scales, with surveys conducted with profile spacing and height-to-ground ranging from 0.1 to 120 m and acquisition frequency ranging between 25 and 500 Hz (Gavazzi *et al.*, 2019).



Figure 2. Comparison between the results of a standard gradiometer survey and a drone borne survey on the Roman site of Odenbourg (France). (A) Pseudo-gradient measured approximately 0,3 m above the ground with a cart-mounted gradiometer array (modified from Reddé *et al.*, 2005); the colorbar is not provided in the original document but data range from 10 nT (white) to -10 nT (black). (B) Total magnetic anomaly measured 1 m above the ground with a drone. (C) Vertical gradient computed from the total magnetic anomaly (B). The results show that the same observations can be done on the drone data after potential field transformation as on the gradiometer data but at a much faster rate of acquisition (x 4). The differences of resolution between the maps is explained by different spacing of the profiles (1 m for the drone survey, 0.5 m for the gradiometer survey).



Through this presentation we aim to illustrate our latest advances in metrology and potential field theory through different results such as a comparison between measured and computed vertical gradient (Fig. 1), a first drone-borne survey achieving ground survey accuracy (Fig. 2), and a new revised depth estimator introducing a form factor to the 2D analytic signal.

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