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GEOPHYSICAL SURVEYING FOR THE DETECTION OF FERROUS-BASED OBJECTS: POSSIBILITIES FOR DEPTH ESTIMATIVE COMBINING ANALYTIC SIGNAL AND VERTICAL INTEGRAL OF THE ANOMALOUS MAGNETIC FIELD

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ABSTRACT. The detection of buried clandestine objects challenges forensic and archeologic search group teams on varying terrains, and variable scales of research. Therefore, the study of controlled buried objects is useful for trainings in geophysical acquisition and processing. In this study, we applied ground survey data for testing the magnetic method at controlled geophysical sites for the location of ordinary objects and firearms. We used data filtering techniques in order to facilitate the location of magnetic targets. Also, we experienced the 3D inversion of analytic signal of the vertically integrated magnetic field (ASVI), for the location of targets in depth. As a result, the study determined the location of four magnetic targets, and a three-dimensional view was constructed from the estimated magnetic susceptibility. We concluded that modeling transformed magnetic data is an affordable technique for application in near-surface investigations. Also, this experiment exemplifies the relevance of magnetic methods for location of excavation sites on the basis of geophysical methods.

Keywords: forensic geosciences; magnetometry; controlled site; buried objects.

INTRODUCTION

Forensic geophysics

Beyond the geological application, geophysical methods have large application on forensic, archeological, environmental, engineering, and military issues. The wide range of application is due to the fact that some objects require noninvasive exploration or cannot be straightforwardly excavated due to unknown location, fragile (archeological sites) or hazardous nature (unexploded ordnance), and locations in high groundwater level (Dupras et al., 2006) and marine areas (Salem et al., 2005). Also, indirect methods for investigation are fast and affordable in producing evidence of buried materials (Blum, 2007; Pringle et al., 2008).

In the scientific forensic search, researchers and forensic experts use principles and practices from geosciences (e.g., geophysics, geochemistry, environmental geology) in the search of evidence in criminal procedures (Ruffell and McKinley, 2005; Lourenço, 2009). The main application is related to crimes against life, environment, nation, and war issues (Pye and Croft, 2004). In the case of clandestine buried materials, complex search may include multidisciplinary techniques, such as multi-method geophysics (France et al., 1992; Pringle et al., 2015), geomorphology (Ruffell and McKinley, 2014) and botany (Aquila et al., 2014). For ordinary cases, buried materials may not be more than 1 m deep, which endorses the use of near-surface geophysical techniques (Pringle et al., 2015).

For exploring the potential application of geophysical methods, controlled sites have been constructed on several research centers. Controlled sites provide professional and undergraduate with the opportunity for geophysical trainings, testing geometrical and compositional characteristics of buried targets, and enhancing acquisition practice and parametrization (Luiz et al., 2007). Such technique has been explored in Brazil on several studies (e.g., Porsani, 2002; Buck, 2003; Rodrigues, 2004; Porsani et al., 2006; Rodrigues and Porsani, 2006; Borges, 2007; De Paula et al., 2007; Luiz et al., 2007; Blum and Russo, 2012; Alves et al., 2013; Buso et al., 2016; Cavalcanti et al., 2018). In the same way, the Laboratory for Research in Applied Geophysics (LPGA) performed researches on forensic studies, initially focused on Ground Penetrating Radar techniques (Bongiolo et al., 2019; Canata et al., 2019, 2020; Canata, 2020). In this work, we bring results of the terrestrial magnetic acquisition for these test sites, in order to exemplify the possibilities of magnetics in the search of ordinary objects and buried firearms.

Magnetic methods for buried objects

Magnetic methods are based on variations of the Earth's magnetic field. Such natural potential field may induce secondary magnetic signals in magnetic bodies. Natural magnetic sources come from geological materials in the Earth's crust, and other perturbations are related to artificial sources, i.e. ferrous-based objects. In this work, we are looking for buried metallic objects, which may also be a factor of disturbance in the natural magnetic field.

Magnetic surveys have long been employed for several noninvasive studies evolving all sorts of ferrous-based buried objects or obstructions, such as the detection of pipes, building structures, metal barrels, and buried weapons. The location and discrimination of such metallic objects are important for civil construction areas, investigation of archeological sites, or mapping unexploded ordnances. In this way, geophysical controlled experiments have been used to explore the feasibility of the detection of possible target (e.g., Cavalcanti et al., 2018; Canata et al., 2020).

However, raw magnetic measurements result in dipolar anomaly maps, which are not off-the-shelf products for interpretation (Rinehart, 2003), especially for intermediate latitudes (Nettleton, 1962). Consequently, techniques for centering natural magnetic anomalies on their sources have been a matter of discussion over the time (e.g., Baranov and Naudy, 1964; Nabighian, 1972; Paine et al., 2001; Li, 2006). In the case of artificial buried objects, two important questions are how the non-centered magnetic feature can be transformed into a well-positioned anomaly over the target and how to model the magnetic source in order to magnetic methods be suitable for application on forensic, archeologic or engineering targets. Moreover, combining different geophysical techniques may overcome limitations of magnetic methods.

Near-surface geophysical sites

The studied area is located in the Polytechnic Center campus of the Federal University of Paraná (Brazil), as part of the Laboratory for Research in Applied Geophysics (LPGA). The test sites have a total of 27 buried artifacts simulating forensic and archeological targets (Figure 1), some of which with high magnetic susceptibility: paint containers with varied metallic objects, metallic drum with varied metallic objects, a plastic drum with small-sized damaged firearms (<20 cm), an empty steel drum, and a pack with damaged rifles (Figure 2). Those ferrous-based targets were buried about 0.30-0.37 m deep. Non-magnetic targets in the geophysical sites are ceramic artifacts, clothes, fossils, and a small fire extinguisher.

The geological background of the geophysical research site is composed by clayey sediments of the Guabirotuba Formation over migmatites and gneiss from the Atuba Complex (Bigarella et al., 1961) as shown in Figure 3. Due to the clayey soil, sand was placed around some artifacts, in order to better understand the impact of those sedimentary backgrounds for the GPR research (Canata, 2020; Canata et al., 2020). However, for magnetic studies, the geophysical signal is unaffected by such soil changes.

METHODS

Magnetic data

The ground magnetic data were acquired at the UFPR geophysical sites on October 23rd, 2019. We used a nuclear precession of proton magnetometer sensor

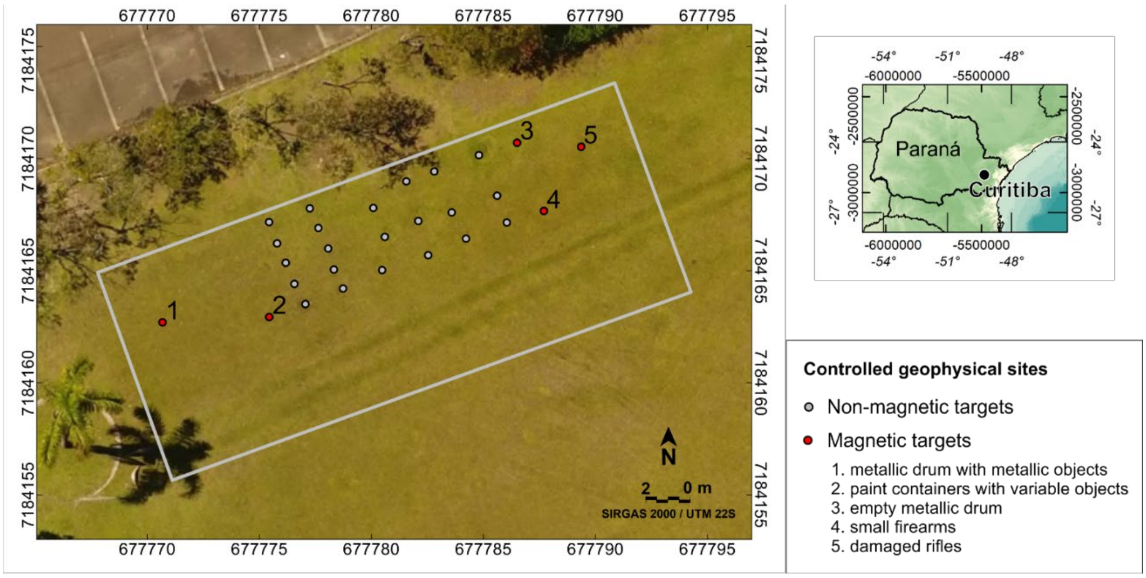

Figure 1: Geophysical test sites in the Polytechnic Center (UFPR), Curitiba, Paraná. The numbers indicate the magnetic test sites. Background image from the Campus Map (Delazari and Ercolin Filho, 2018; http://www.campusmap.ufpr.br).

Figure 2: Magnetic materials buried in the controlled sites: 1 and 3 metallic drums with metallic objects and empty, respectively; 2- paint container with varied metallic objects; 4- a plastic drum with small-sized damaged firearms (<20 cm); 5- a pack with damaged rifles.

(GEM-Systems GSM-19T magnetometer) supported by two-person teams. The daily variation was measured with an ENVI-VLF MAG magnetometer (Scintrex) in a fixed base. After acquisition, the data were processed by the LPGA Team using Oasis Montaj™ tools for corrections and manual leveling. The leveled data show final crossing errors about 11 nT. The final dataset has 552.39 meters of leveled data, distributed as 34 lines and 8 tie-lines. The magnetic data and acquisition report are available in the UFPR scientific data repository (Bongiolo et al., 2021, available at https://hdl.handle.net/1884/72869).

Data filtering

The data filtering was applied in the total field anomaly (TFA) for making comprehensive magnetic maps, and also transforming the TFA in suitable data for modeling. In this case, we applied the following filters: reduced-to-pole (RTP - Baranov, 1957; Baranov and Naudy, 1964), analytic signal amplitude (ASA - Nabighian, 1972; Roest et al., 1992), and vertical integral (VI - Silva, 1996). All filters were performed in the Oasis Montaj™ software.

For the RTP filter, the procedure consists of emulating the magnetic anomaly for the Earth's pole conditions (Baranov and Naudy, 1964), where field lines are about 90º and the magnetic declination is zero. In this condition, magnetic dipoles may have the maximum amplitude for the positive part, as well as show the minimum negative amplitude (Nettleton, 1962). As a result, the magnetic anomaly has a major positive expression, which may be centered over the magnetic source. In order to achieve this goal, we should inform parameters of the total magnetization vector. Assuming a negligible remanence, those parameters

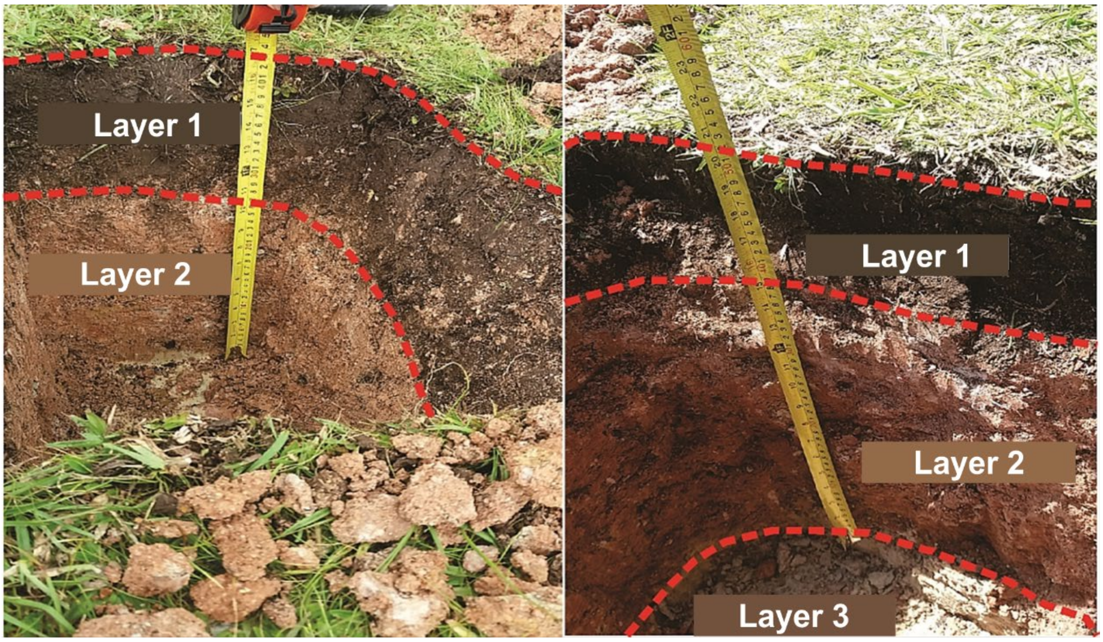

Figure 3: Controlled site soil profile (Canata, 2020). Layer 1: organic soil (0 – 0.2m); Layer 2: clay soil (0.2 – 0.7m); Layer 3: silty soil (0.7 – 1.0m).

can be estimated on the basis of the International Geomagnetic Reference Model Field (IGRF; Thébault et al., 2015). The RTP filter can be expressed as showed in equation 1 (Grant and Dodds, 1972; MacLeod et al., 1993a, 1993b; Li, 2008):

$$\mathrm{RTP}(\theta) = \frac{[\sin(I) - i\cos(I)\cos(D-\theta)]^2}{[\sin^2(Ia) + \cos^2(Ia)\cos^2(D-\theta)]\cdot[\sin^2(I) + \cos^2(I)\cos^2(D-\theta)]} \tag{1}$$

where I = inclination, D = declination, θ = wavenumber, and Ia corresponds to the pseudo-inclination. This last variable was applied for solving the magnetic response of sources on low latitudes. In our case, the estimated declination and inclination were -19.8º and -38.2, respectively, and the Ia was -51.8º.

The ASA filter constitutes an alternative technique for centering positive anomalies over their sources (Nabighian, 1972). The advantage of this method relies on avoiding the assumption of magnetization parameters, since it is self-ruled by the relation between magnetic field's derivatives (Eq. 2), where $\partial x, \partial y$ and ∂z are the derivatives in the x-, y- and z- directions, respectively. Consequently, this filter tends to emphasize the shallow response.

$$\mathrm{ASA} = \left[\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2 + \left(\frac{\partial M}{\partial z}\right)^2\right]^{1/2} \tag{2}$$

On the other hand, the vertical integration of the magnetic field is used for enhancing deep magnetic sources (Silva, 1996). The combination of ASA and VI tend to be suitable for modeling, since the decreased high-frequency content may simplify the model fitting, the anomalies tend to be centered over their magnetic sources, and the result is given in nT (Paine et al., 2001). ASA and VI are arranged as the analytic signal amplitude of the vertically integrated magnetic field (ASVI), and the vertical integral of the analytic signal amplitude of the field (VIAS). Due to the vertical integration, the content of large wavelengths was increased especially on VIAS data. The enlargement of anomalies by the VIAS filter (regarding the total field anomaly) was demonstrated with a synthetic dyke model in Paine et al. (2001). In any case, both VIAS and ASVI seem to be useful for the estimation of unknown targets, and this study was an opportunity to explore the usability of those filters.

3D modeling

Three-dimensional models for magnetic susceptibility variation were constructed for testing depth estimative with the input of transformed magnetic data. We tested RTP, ASVI and VIAS grid as data input for modeling, which contributes for expanding the discussion of ASVI and VIAS filters on literature.

For this inversion, we used the VOXI Earth Modeling, in the Oasis Montaj™ software. The three-dimensional inversion was unconstrained, using a 0.55 m mesh grid and a base ~5m deep. Since the magnetization parameters of unknown magnetic objects cannot be previously estimated by the interpreter, the susceptibility variation was not limited in a specific range. Moreover, the model had no initial model, due to the magnetically neutral geological background. The local ambient field was settled with field intensity from the IGRF model (22610 nT), and all models (RTP, ASVI and VIAS) were done with the ambient field settled as the polar magnetic field (inclination and declination as 90º and zero, respectively). Such assumption was done since the ASVI and VIAS had theoretically centered the magnetic dipoles. Also, it was assumed a polar-like magnetization for these anomalies (Paine et al., 2001).

For the comparison of the resulting three-dimensional models, the values were transformed in order to adjust the diverse origin values (RTP, ASVI and VIAS) to a theoretically common scale. Firstly, the values were standardized by subtracting the median from each one, and then they were divided by the standard deviation. Subsequently, the standardized variables were normalized by the min-max method, which subtracts the minimum value from each item, and divides by the difference between maximum and the minimum values. Afterwards, we considered values over three times the standard deviation as anomalous values.

RESULTS

Magnetic maps

The magnetic maps (Figure 4) show two high-amplitude anomalies to the west, which clearly correspond to the metallic drum with varied metallic objects (magnetic site 1, Figure 1) and paint containers with varied metallic objects (magnetic site 2, Figure 1). In the top right corner, relatively lower magnetic anomalies are shown, and even smaller amplitude variations are observed in the center of the area. From the filtered maps (ASA, VIAS and ASVI on Figures 4e, 4g and 4h, respectively), it is possible to distinguish the anomaly from the magnetic site 5 (Figure 1). Meanwhile, magnetic sites with a metallic drum (magnetic site 3, Figure 1) and a plastic drum with small firearms (magnetic site 4, Figure 1) have relative lower magnetic amplitudes, which could even be interpreted as minor variations, and could be ignored in a non-controlled study case, for instance.

In comparison to the RTP map (Figure 4d), the ASA filter (Figure 4e) improved the similarity between the positive magnetic anomaly on the map and the effective geometry of the target. In the same way, the VIAS (Figure 4g) and the ASVI (Figure 4h) are well presenting the location of the controlled magnetic sources. We noticed higher magnetic amplitudes on the VIAS (Figure 4g) map. On the other hand, ASVI (Figure 4h) data have a similar anomaly amplitude to the TFA (Figure 4a) and RTP (Figure 4d) ones.

3D models

In Figure 5, it is possible to compare the ASVI and VIAS models with the RTP inversion result. It is noticed the base of the anomalous areas up to ~2m deep, while the real targets were based into the first meter under the surface. For the magnetic sites 1 and 2 (Figure 1), the elongation of the modeled targets is in agreement with the geometry of the buried objects in the ASVI and VIAS results, but the elongation is transverse in the RTP result. In the magnetic site 5 (Figure 1), the body is out of place in the RTP result, but the location is reasonable in the ASVI and VIAS results.

The normalized result from the three-dimensional inversion reveals three main anomalous areas in the spatially distributed magnetic susceptibility (Figure 5), which recovered three of the five magnetic sources: the metallic drum with metallic objects (site 1, Figure 1), the painting containers (site 2, Figure 1), and the damaged rifles (site 5, Figure 1). There was no significant result for targets 3 (Figure 1, the empty metallic barrel) and 4 (Figure 1, the small weapons) in this 3D inversion.

DISCUSSION

Detectability of magnetic targets

Two high-amplitude magnetic anomalies are clearly associated to sites 1 and 2 (Figure 1), and the dipolar settings are in accordance with the induced field in the southern hemisphere. Consequently, both targets were also well defined in the 3D models (Figure 5). Conversely, merged small-amplitude anomalies in the eastern part do not allow a straightforward linkage between anomalies and magnetic targets on the TFA (Figure 4a) and VI (Figure 4f) maps. Nevertheless, the filtered magnetic ASA (Figure 4e), ASVI (Figure 5a) and VIAS (Figure 5b) maps located the positive anomalies over these Fe-based sources (Figure 5).

The magnetic site 4 (Figure 1, small firearms) was little recognizable on the maps, and it was not recovered in the magnetic modeling. However, the damaged rifles on site 5 (Figure 1) were recovered in the ASVI 3D model (Figure 5a). Regarding the dimensions and positioning of those metallic items, the firearms on site 4 are randomly arranged and small-sized, while on site 5 they are elongated and parallelly assembled.

Consequently, we interpret that the detectability of sites 5 and 4 (Figure 1) are ruled by the setting and the size of the buried firearms. The physical arrangement of

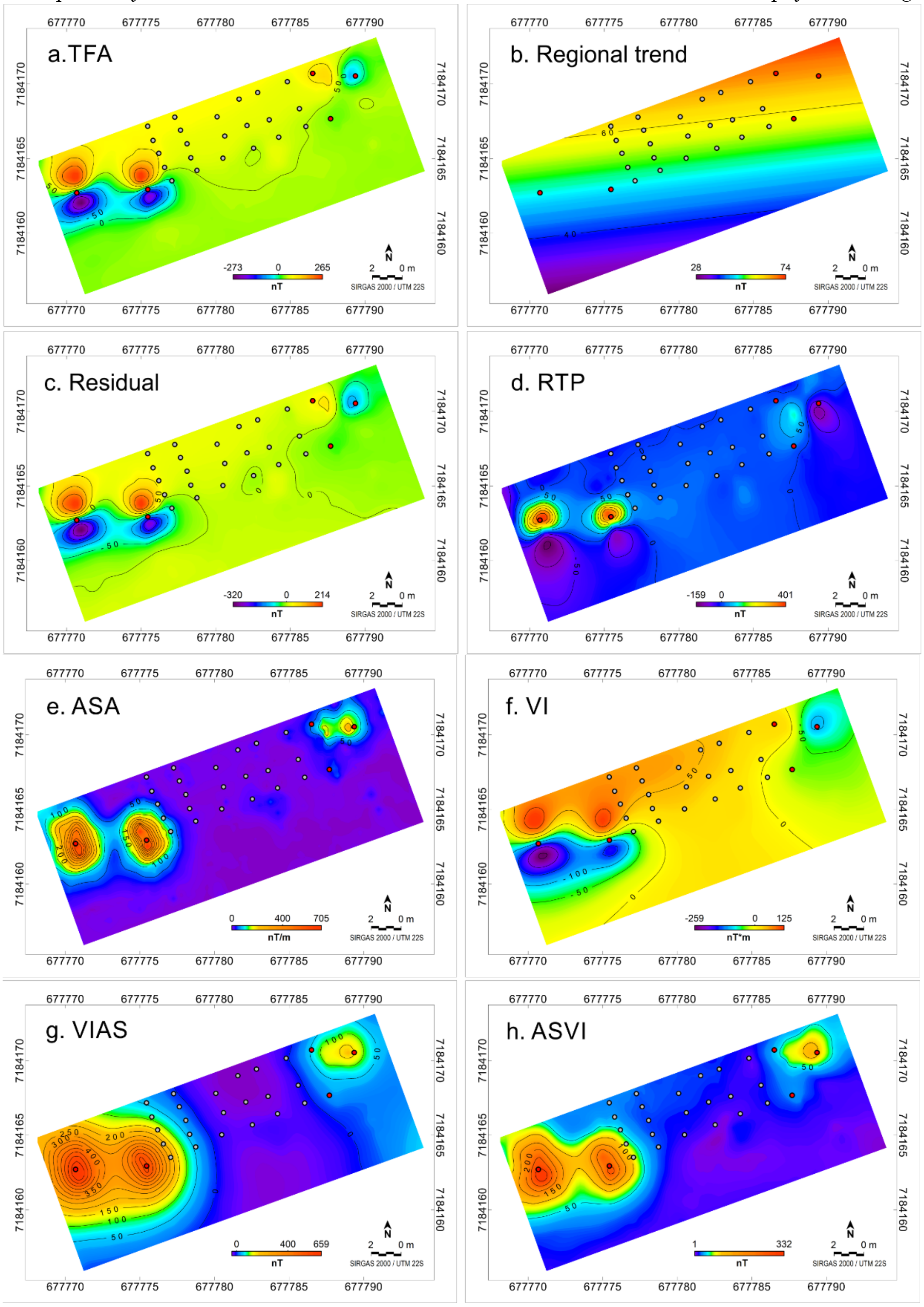

Figure 4: Magnetic data maps. (a) TFA - total field anomaly. Filters applied in the residual TFA grid: (b) Regional trend; (c) Residual; (d) RTP; (e) ASA - analytic signal amplitude; (f) VI - vertical integral; (g) VIAS - vertical integral of the analytic signal amplitude; (h) ASVI - analytic signal amplitude of the vertically integrated field.

the firearms on test site 5 (Figure 1) may facilitate the convergence of the ambient magnetic force lines into the target. Conversely, the small size of the metallic objects on site 4 (Figure 1, <20 cm), and the random spatial orientation of those objects (Figure 2) might reduce the detectability of this target.

Analyzing the two buried metallic drums, it was observed a strong magnetic response on magnetic site 1 (Figure 1), and a very low amplitude magnetic anomaly on magnetic site 3. The contrastingly magnetic signature is interpreted as the effect of the magnetic content into the metallic drum from site 1 (Figure 1), while magnetic site 3 (Figure 1) has only the thin cylindric sheet. From the literature, the standard three-dimensional calculations for magnetic modeling of geological bodies expect massive bodies or even moderate thin sheets. Therefore, thin magnetic sheets could be numerically problematic for modeling, and need specific model calculations (Eskola et al., 1993). Despite the low detectability of one empty metallic drum, an assemblage of Fe-based drums is feasible on larger scale environmental studies, for instance (Marchetti et al., 1998).

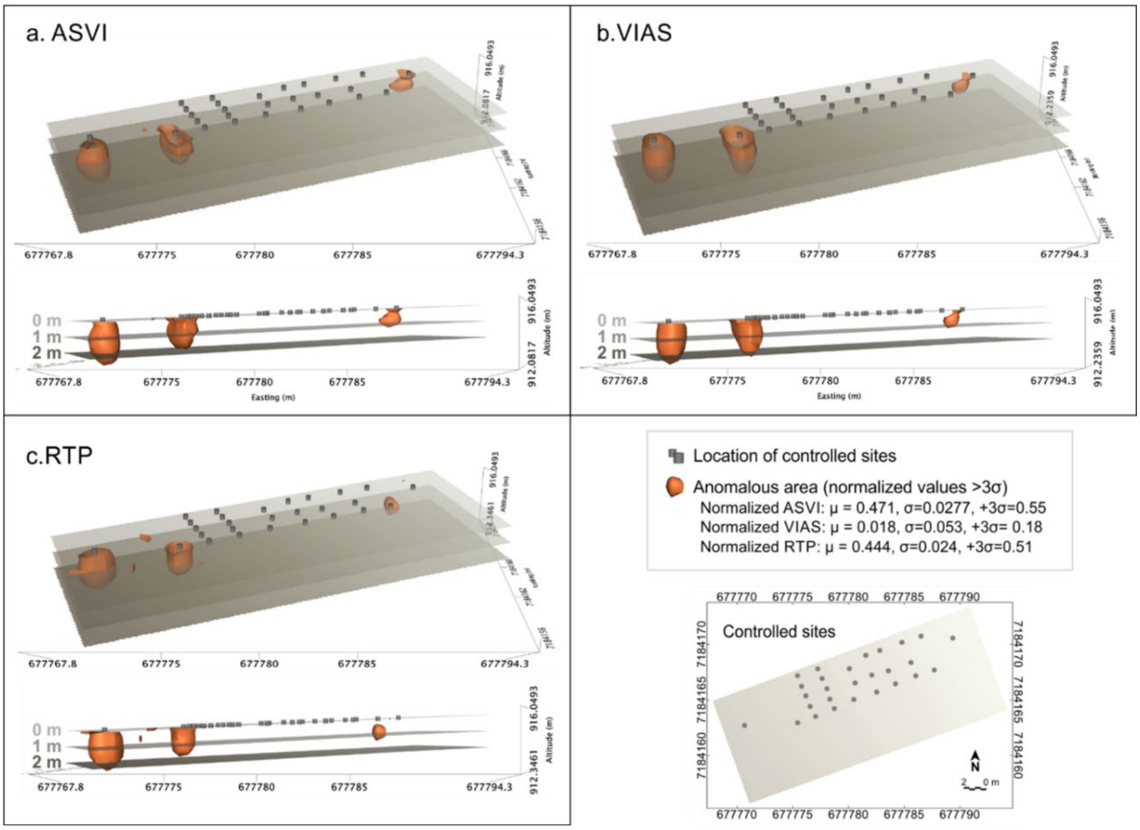

Figure 5: 3D models for the location of Fe-based targets (normalized contrasting susceptibility). Results from the inversion of the ASVI (a), VIAS (b) and RTP (c) data.

Inversion result and the usability of ASVI and VIAS data for modeling

On Figure 5, isolated bodies correspond to anomalous values (+3σ). Targets 1 and 2 (Figure 1) were reasonably recovered in all models, but target 5 (Figure 1) was better located in the ASVI model (Figure 5a). The depths of the targets were a bit overestimated in all models. However, we considered the results are suitable for the location of the targets.

From the anomalous areas, it is noticed that the RTP inversion (Figure 5c) formed some mistaken minor anomalies near to the surface, while it is absent in the ASVI (Figure 5a) and VIAS (Figure 5b) results. It is plausible to assume that the vertical integration in the ASVI and VIAS work as a filter for reducing their high-frequency content, avoiding those minor shallow artifacts. Confronting the RTP result (Figure 5c), recovered bodies in the ASVI and VIAS models (Figures 5a and 5b, respectively) are best fitted as the expected position and elongation of the studied metallic objects.

Regarding the concern about using transformed data (ASVI and VIAS, Figures 5a and 5b, respectively) for modeling instead of the classical RTP or the TFA itself, this practical experiment indicates that these filters could be used as input for magnetic modeling. Furthermore, the ASVI and VIAS results (Figures 5a and 5b, respectively) are comparable with the results from the RTP (Figures 5c), in terms of maximum depth (~2 m) and top of the 3σ anomalies.

On quantitative modeling, there are techniques for handling effects of remanence in the magnetic source (e.g., inversion of magnetic vector - Ellis et al., 2012), which allow the refinement of TFA and RTP data for modeling. However, ASVI and VIAS likely work as an affordable alternative for students and professionals since their construction is based on standard filters in magnetic data processing (ASA and VI). Also, their straightforward representation of anomalous areas on maps is desirable for understanding the magnetic source considering the qualitative magnetic interpretation.

Accordingly, we conclude that the application of ASVI and VIAS as input for 3D inversion is acceptable for predicting near-surface targets, and they may be useful, for instance, in forensic, environmental, and archeological investigations.

CONCLUSIONS

We tested the magnetic response of assembled firearms and ordinary magnetic objects in the controlled test sites of the Federal University of Paraná. This study demonstrates that controlled geophysical test sites are useful for observing perturbations in the total magnetic field caused by ferrous-based materials, and for testing in-depth investigation techniques. We interpret that the detection of minor magnetic targets relies on the combination of physical arrangement and size of these objects. Regarding the filtered data, we conclude that both combinations of analytic signal amplitude and vertical integration filtering (ASVI and VIAS) were effective as data input for modeling magnetic sources. Therefore, ASVI and VIAS transformed data are likely applicable for estimation of near-surface magnetic targets in forensic investigations.

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