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# Real magnetic stripping method in unexploded ordnance detection and remediation – a case study from Rohožník military training range in SW Slovakia

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**Abstract:** In this contribution we present results from a case-study, which was performed in collaboration between geophysicists and explosive ordnance disposal technicians at the Rohožník military training range in SW Slovakia. The aim of this study was to locate a deep-penetrated unexploded Mk-82 aerial bomb using high-definition digital magnetometry. The location where this bomb had entered the ground was known but its final position needed to be determined so that a safe excavation and disposal could be conducted. However, the detection of this unexploded ordnance object was complicated by the presence of intense magnetic interference from a number of near surface ferrous items including non-explosive test bombs, fragmentation and other iron junk. These items contributed a localised, high amplitude of magnetic clutter masking any deeper source. Our strategy was to approach the problem in three stages. First, we used magnetic data to locate the near surface items. After the detection and before the excavation of the searched objects, two quantitative interpretation methods were used. These involved an optimised modelling of source bodies and the application of a 3D Euler deconvolution. Both methods yielded acceptable results, but the former was found to be more accurate. After the interpretation phase, many of the items were then safely excavated and removed individually. A second magnetic mapping was then performed and from this data which was now significantly less cluttered, we were able to identify but not quantify, two deep source items and to confirm that all remaining near surface items were significantly smaller in size than a Mk-82 bomb. As the remaining near surface sources were interpreted as being contained within the surface one metre of soil and being small they could be assured to

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be non-explosive, it was considered most practical to mechanically excavate and remove this soil and the remaining objects contained. With the magnetic interference from these items now eliminated, we re-mapped the site a third time and were then able to not only detect, but precisely quantify the position and depth of two deeper items, one of which was the Mk-82 bomb that was the target of our search, the other an intact, non-explosive practice bomb. These were both then excavated and removed and the Mk-82 bomb destroyed by the explosive ordnance disposal experts from the Rohožník military training range. The study title "real magnetic stripping" reflects the strategy that we adopted.

**Key words:** magnetometry, UXO, modelling, stripping, Marquardt algorithm, Euler deconvolution

## 1. Introduction

Geophysical methods play an important role in the detection of unexploded ordnance (UXO). The most used geophysical methods involve detailed magnetic and/or electromagnetic (EM) measurement. Advances in the development of magnetometers over the last decades has made these instrument systems particularly efficient in rapidly acquiring very detailed, "high definition" magnetic mapping data from which ferrous items can be detected and their position quantified. Magnetometry is now used worldwide as a state-of-the-art technology applied to UXO detection (e.g. *Robitaille et al., 1999; Youmans et al., 2002; Stanley and Cattach, 2004; Billings and Youmans, 2007*). Magnetometer systems are readily adaptable to be carried by hand, pushed manually on wheel-carts, pulled behind small vehicles and there have been several successful trials with sensors mounted on Unmanned Aerial Vehicles (UAV's or drones). (e.g. *Nikulin and de Smet, 2019; Kolster and Døssing, 2021*). In this present case study, we used a single, Cs vapour type magnetic sensor, carried by hand.

The interpretation of magnetic datasets has required methods for precisely determining target location and of reliably estimating its depth and size. An accurate depth estimation is important for safety reasons as this can help Explosive Ordnance Disposal (EOD) technicians to choose the best method of digging and extracting the detected objects. Similarly, an accurate size estimation is also very important, because it can help to distinguish between larger objects (potentially live ordnance) and smaller objects such as fragmentation. A principal driver of cost in UXO site remediation is the investigation of false alarms due to fragmentation and other inert, ferrous items. There exist a variety of quantitative interpretation methods which can be applied to achieve the required interpretation characteristics. Of these, magnetic modelling (e.g. *Butler, 2001*) and deconvolution methods (e.g. *Davis et al., 2010*) are the most commonly used. We also used these two methods for the estimation of position, size and the depth of detected targets. In our modelling we first calculated the parameters of a simple magnetic dipole that best fitted our observed data and then refined this by fitting an ellipsoid of similar dimensions (*Clark et al., 1986*). We also applied a classical 3D Euler deconvolution to the measured data (*Reid et al., 1990*). We first tested both mentioned methods on a synthetic data-set and then applied them in the real-world situation, on magnetic data acquired from the Rohožník military training range near the town of Malacky in SW Slovakia.

At the Rohožník range various types of aerial ordnance are periodically dropped for training purposes. For safety reasons, any that fail to explode are then to be relocated and removed. In this paper we present results, obtained in the framework of a scientific collaboration among the Department of Applied Geophysics (Comenius University), the G-trend Ltd. company and military EOD experts from the Rohožník military training range. Our objective was to locate one aerial bomb Mk-82, which was likely to have penetrated to a depth of several meters during bombing practise and which had remained unexploded. The task was made challenging because the anomalous magnetic field associated with the bomb was expected to be deformed and masked by numerous, more intense anomalies coming from shallower objects which included pieces of non-explosive practise ordnance, fragmentation from exploded ordnance and debris from bombing targets. For this reason, our magnetic measurements were performed in three stages with the aim of the first two stages being to detect and locate these shallow interfering objects so that they may be safely removed physically from the searched area. In gravimetry, there exists concept of subtraction of the calculated effects of known sources from the measured field, to enhance the response from unknown sources of interest. This practice has been referred to as analytic "stripping" (e.g. *Bielik et al., 2013*). In our case we suggest the name "real magnetic stripping", because in our application the interfering source objects first detected, were physically removed from the studied site before conducting a subsequent survey.

The approximate position of the Mk-82 bomb that was our target was known from its impact crater and so our investigation could be constrained to an area measuring 20 × 20 m. The acquisition of high-definition magnetic data over such a small area was a minor component of the task and the conduct of three surveys provided a cost-effective solution. After the first survey, the most intense of the anomalies were analysed. These were all interpreted as having a relatively small source compared with a Mk-82 bomb and all were near surface. These objects were then excavated by EOD technicians by hand. With the most intense sources removed, the second stage survey was conducted, with the aim of checking the excavation results and of detecting the deeper objects. Even with the most intense sources now removed, the magnetic interference from a large number of remaining small sources prevented the reliable calculation of the position and depth of the deeper target of interest although its presence could now be observed. However, the data from the second survey did enable an important and reliable conclusion to be drawn. This conclusion was that all the remaining sources of interference were located within 1 m of the surface and none of these posed any threat of being hazardous. With this information, it was deemed safe and most cost-effective to use a mechanised excavator to remove the top metre of soil from the central 15 × 15 m area of the site. This was done using equipment belonging to the Rohožník range. Upon removal of the top metre containing all the remaining sources of magnetic interference, the third phase of measurements were performed on the new surface. From this final measurement we were able to precisely interpret the position and depth of the target Mk-82 bomb. This was then excavated, removed and destroyed by the EOD experts from the Range.

## 2. Methods

In high-definition magnetic surveys for UXO detection, Cs-vapour and flux-gate magnetometer systems are often used. In this case study we used a TM-4 magnetometer system with one hand-carried Cs-vapour Geometrics sensor (model G822AS) providing a resolution of ±0.1 nT. Data acquisition was performed along lines separated by 0.5 m with a sampling interval of approx. 0.1 m along lines. We used a local coordinate system (x = Easting, y = Northing), and the measurement interval along lines was automatically determined using a digital, cotton thread-based odometer device. After data acquisition, the measured values of the total magnetic induction (T) were filtered by means of a median filter (to remove heading errors and the long-term Earth magnetic field variations) and a low-pass Butterworth filter (for removing instrumental noise and the short-term Earth magnetic field variations). The regional magnetic field was removed during the median filtering procedure and the resulting $\Delta$T values were interpolated into a $0.1 \times 0.1$ m grid using the Kriging method (with a linear variogram). The resulting $\Delta$T grid data were interpreted using both qualitative and quantitative approaches. During qualitative interpretation the detected anomalies of interest were identified by their dipole character, wavelength and amplitude. A quantitative interpretation procedure was then applied to these target anomalies to estimate the position and depth to their magnetic source.

We used two independent methods to determine the source depth. The first one was based upon an optimisation modelling procedure, during which a simple magnetic dipole was first fitted to the observed data. This dipole model was then refined using an ellipsoid model which was best fitted to the observed data using a nonlinear least-squares method after *Marquardt (1963)*. This optimisation search is automatically performed within a small, selected area around the selected anomaly (using MAGSYS software developed at the Geophysical Research Institute in Armidale, Australia). While the estimation of the dipole parameters serves as a first approximation to the solution, the search for an ellipsoid gives more accurate results. Within the process, dimensions of such an ellipsoid are based on the a-priori knowledge of the searched ordnance type (important are the length and the diameter of the ordnance). The assumed magnetic susceptibility of the steel from which the ordnance was manufactured was set to an average value of 10 [SI units]. The output from MAGSYS was the grid location and depth to the centre of the best fit to the measured data of the ellipsoid options contained in the ordnance database.

The second method used classical 3D Euler deconvolution (*Reid et al., 1990*) with the introduction of regularized derivatives (*Pašteka et al., 2009*). Euler deconvolution or simply the Euler method is based on the Euler homogeneity theorem, which is valid for potential fields including the geomagnetic field. The result is represented by a group of depth estimations, each solution being obtained for a different position of the interpretation window.

These individual estimations can be expected to cluster in close proximity to the source position. The Euler deconvolution method requires the character of the source to be defined by a special parameter, called structural index (SI). An SI of 3 is appropriate to a pure dipolar magnetic source. Sometimes non-integer SI values are used (this approach was criticised by *Reid and Thurston, 2014*) – some authors consider the value 2.5 best represents UXO objects which are closer to elliptical than dipolar (e.g. *Paoletti et al., 2019*). The interpretation window size is usually 10 × 10 grid points and the calculated depth solutions are sorted according to the values of their standard deviations (in-house Matlab software REGDER, *Pašteka et al., 2009*). Focused clusters of depth solutions give the depth of the centre of the source.

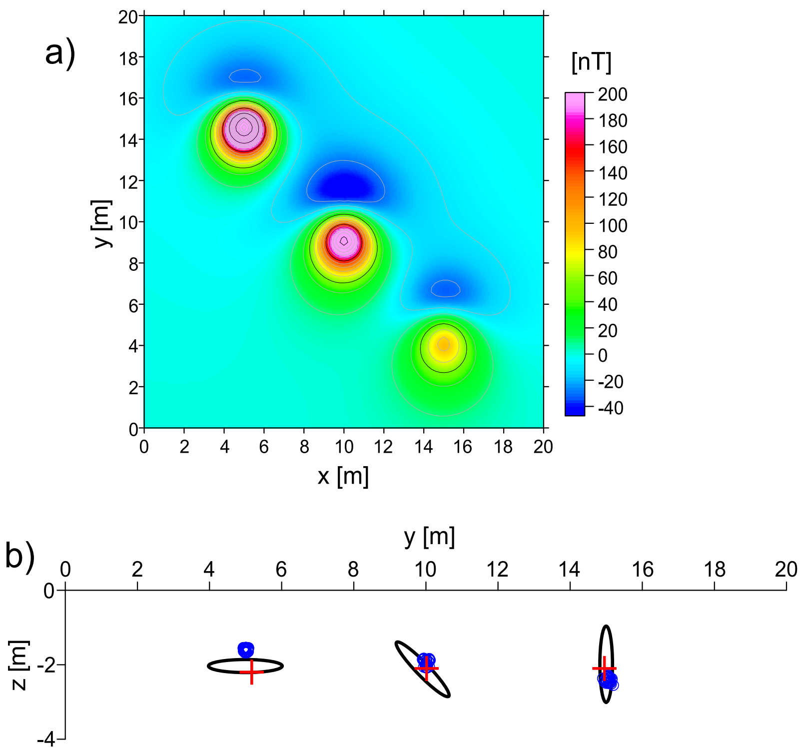


Fig. 1. Results of the depth estimations applied to synthetic, ellipsoidal models of different orientation. (a) map of the ΔT field generated by the synthetic models; (b) depth estimates from the Marquardt's algorithm fitting a magnetic ellipsoid (red crosses) and 3D Euler deconvolution (groups of blue circles).

In order to demonstrate the capabilities of the two interpretation methods that we proposed using on our field data (i.e. the Marquardt optimisation modelling and the 3D Euler deconvolution) we first interpreted the data generated from three synthetic models. These models represented ellipsoids, dipping in different angles to the horizontal plane, and each at a depth of 2 m (Fig. 1). The dimensions of all the three ellipsoids were chosen to represent a Mk-82 aerial bomb. The ellipsoid length was 2,220 mm and the diameter was 273 mm (https://en.wikipedia.org/wiki/Mark_82_bomb). Only induced magnetisation of the ellipsoidal objects was assumed, with an inclination of 65° and declination of 0°. As it can be seen in Fig. 1, both methods have given very good and reliable results. The depth error observed using Euler deconvolution was within approximately 10−15% of the true depth, while the error in results using optimisation modelling was significantly less than this.

## 3. Analysis of stage 1 of the magnetic survey at Rohožník military training range

In the first stage of the magnetic survey we have delineated a 20 × 20 m square around the place where the unexploded bomb Mk-82 penetrated the ground, which was clearly visible at the surface as a small impact crater. The EOD technicians from the Rohožník military training range were convinced that the actual position of the bomb should be located within the limits of this square. Magnetic mapping of this area was conducted as previously described. Given the small search area involved, the time and cost of this magnetic mapping was a trivial component of the remediation budget. The magnetic field, $\Delta$T is presented as a colour image in Fig. 2. The most significant anomalous targets in terms of wave-length and amplitude were then interpreted using the two methods described. The positions of all interpreted targets are shown as numbered crosses in Fig. 2. There were 20 of these and the 15 closest to the point of entry of the Mk-82 were selected for excavation by EOD technicians from the Rohožník military training range. The results of this investigation are recorded in Table 1. Other smaller anomalies detected were assumed to be caused by fragments of previously exploded ordnance objects at the Range and were considered non-hazardous. Several objects (objects nos. 7, 12, 16 and 17) in the upper-left corner of

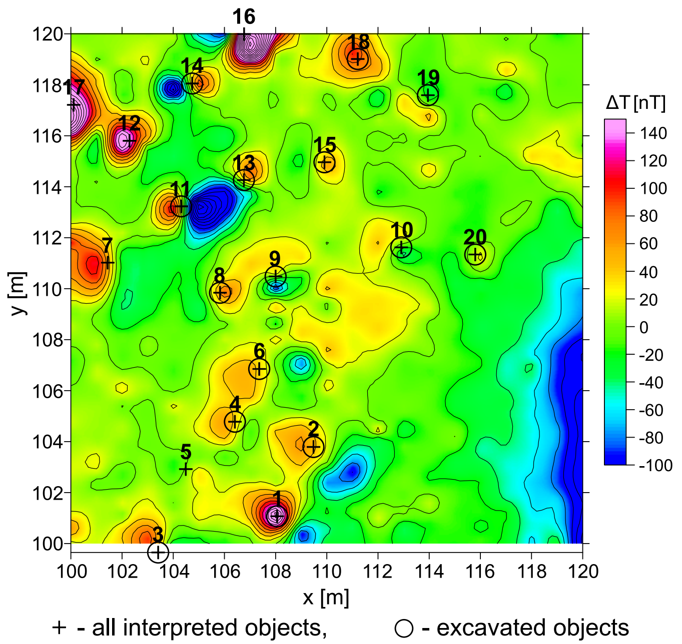


Fig. 2. Map of the anomalous magnetic induction field ΔT, acquired during the first stage of a high-definition magnetic survey within the studied area. Numbers denote the interpreted local magnetic anomalies (objects), summarized in Table 1.

the area were left in the ground, in part because of their larger distance from the point of penetration and in part due to a misunderstanding of the need to excavate them by the EOD technicians. Object no. 5 was not found by the EOD technicians, it was probably a fragment of small dimensions, which was removed during digging a hole and then lost. The large negative anomaly in the bottom-right corner of the ΔT map (Fig. 2) resulted from a nearby parked car – a "green-horn" mistake, for which we deeply apologize to the readers!

Objects no. 1 and 2 were found to be non-explosive test aerial bombs with inert concrete filling (approx. length 1,000 mm, diameter 200 mm). Object no. 11 was a large piece of iron junk, a part of a former firing target. Remaining objects were iron fragmentations from test bombs or target objects destroyed in the past. No explosive ordnance was found in this first stage of the survey. The comparison between the calculated depth estimations of the detected objects with their actual excavated depths is

Table 1. Positions and depths (estimated and true) of the interpreted objects from first stage of the survey in Rohožník Shooting Range.

| Nr. | x [m] | y [m] | depth (model.) [m] | depth (Euler) [m] | depth (true) [m] | excavated object |
|---|---|---|---|---|---|---|
| 1 | 108.06 | 101.07 | 0.5 | 0.7 | 0.6 | test bomb |
| 2 | 109.48 | 103.79 | 0.7 | 1.0 | 0.8 | test bomb |
| 3 | 103.41 | 99.65 | 0.3 | 0.2 | 0.2 | fragment |
| 4 | 106.41 | 104.78 | 0.4 | 0.2 | 0.2 | bomb fuse |
| 5 | 104.49 | 102.92 | 0.4 | 0.5 | not excavated | fragment? |
| 6 | 107.36 | 106.85 | 0.6 | 0.7 | 0.2 | fragment |
| 7 | 101.44 | 111.02 | 0.6 | 0.7 | not excavated | test bomb? |
| 8 | 105.83 | 109.84 | 0.1 | 0.2 | 0.1 | fragment |
| 9 | 108.00 | 110.48 | 0.1 | 0.1 | 0.1 | fragment |
| 10 | 112.91 | 111.62 | 0.7 | 0.2 | 0.2 | fragment |
| 11 | 104.31 | 113.23 | 0.1 | 0.5 | 0.5 | iron junk |
| 12 | 102.29 | 115.80 | 0.4 | 0.4 | not excavated | fragment? |
| 13 | 106.76 | 114.26 | 0.1 | 0.3 | 0.1 | fragment |
| 14 | 104.74 | 118.05 | 0.1 | 0.3 | 0.1 | fragment |
| 15 | 109.91 | 114.96 | 0.1 | 0.5 | 0.2 | fragment |
| 16 | 106.77 | 119.99 | 0.4 | 0.7 | not excavated | test bomb? |
| 17 | 100.11 | 117.21 | 0.5 | 0.5 | not excavated | test bomb? |
| 18 | 111.21 | 119.01 | 0.7 | 0.8 | 0.3 | fragment |
| 19 | 113.95 | 117.59 | 0.1 | 0.3 | 0.1 | fragment |
| 20 | 115.80 | 111.34 | 0.3 | 0.4 | 0.1 | fragment |

recorded in Table 1. This gives a good overview of the properties of both interpretation methods used. The optimisation modelling method (program MAGSYS) delivered a median of the relative differences against to the true depth on the level of ±50%, while in the case of the Euler method (program REGDER) it was ±100%. The medians for the simple differences (absolute values) were 10 cm and 20 cm for the first and the second methods, respectively. From these simple statistics it is clear that the first method gave more reliable depth estimates. Reliable depth estimates are very important for the safety of EOD technicians who can use this information to adjust their excavation methodology when approaching to the expected depth of the object.

After this "real magnetic stripping" (physical removal of the majority of the near surface sources) the area was re-mapped in the second stage of the survey.

## 4. Analysis of stage 2 of the magnetic survey at Rohožník military training range

After the excavation of all selected objects from the first stage investigation (Fig. 2, Table 1), the 20×20 m square area was re-mapped. Data acquisition and processing of the measured data were performed in the same way, as it was in the first stage and a new map of anomalous magnetic field ΔT was prepared (Fig. 3). This second stage was understood as a quality control stage to confirm that the objects selected for excavation were all removed. It also provided the next step in the search for deeper objects previously masked by the items removed. As it can be seen from the character of the

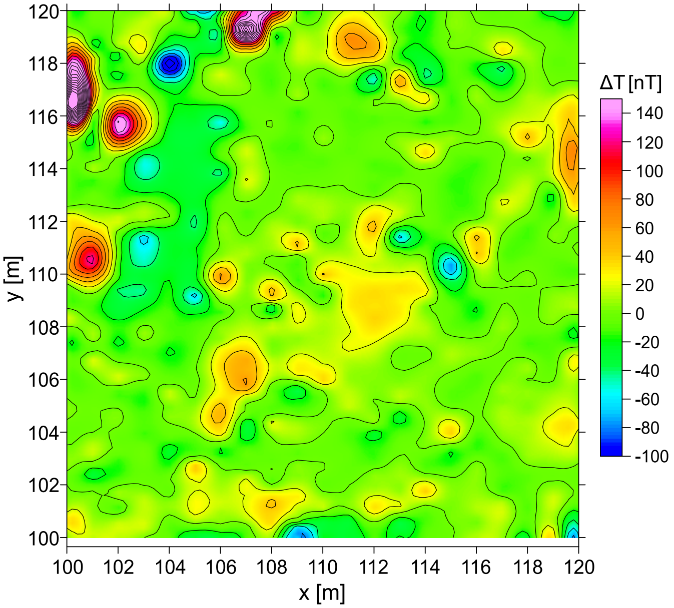


Fig. 3. Map of anomalous magnetic induction field ΔT, acquired during the second stage of high-definition magnetic survey at the studied area.

obtained anomalous magnetic field (Fig. 3), the central part of the area was in the majority "cleaned" from the near surface objects, while the five targets in the upper left corner that were not excavated remain. From the anomalous field in Fig. 3 it can also be seen that objects 4, 8, 14 and 18 were not entirely removed, with some rust and very small flakes of fragmentation remaining in the ground.

With the magnetic clutter now reduced from the central region of the second stage map (Fig. 3) two anomalies with longer wavelengths, suggesting greater depth can be recognised. But the signal-to-noise ratio was too low to permit a reliable interpretation. The left-hand anomaly could be associated with some residue from the formerly excavated object no. 6 but to draw this conclusion could result in the hazardous risk that a dangerous item was overlooked. In an attempt to resolve this ambiguity, we calculated a 0.5 m upward continuation of this data deploying the standard Upward Continuation filter routine in the Fourier spectral domain, using the Matlab script REGCONT2 (*Pašteka et al.*, 2018). In the upward continued field presented in Fig. 4, it can be seen that these two anomalies now have better developed shapes that can be better interpreted in a qualitative way. In Fig. 4 we have identified their local maxima by triangles. As an expected result of the Upward Continuation (UC), the effects of shallower objects are more attenuated than those of deeper objects. The fact that Upward Continuation did not attenuate either of these sources provides evidence that there are in fact two deep source objects and these both must be investigated. However, remaining disturbance from near surface sources prohibited a reliable quantitative interpretation as desired before any excavation was attempted. We did apply both interpretation methods to this disturbed data, and they each gave a depth estimate to source of more than 1 m for the left-hand target and more than 2 m for the one on the right. But we considered these estimates as only of informative interest. We did not wish to rely upon them.

One conclusion from this second stage data that we could rely upon was that there would be no hazardous objects within one metre of the ground surface in the central area of the search. We could therefore safely and economically strip the top 1 metre of soil using machinery available on the Range. This was done over a 15 $\times$ 15 m area and then Stage 3 of our magnetic mapping was performed.

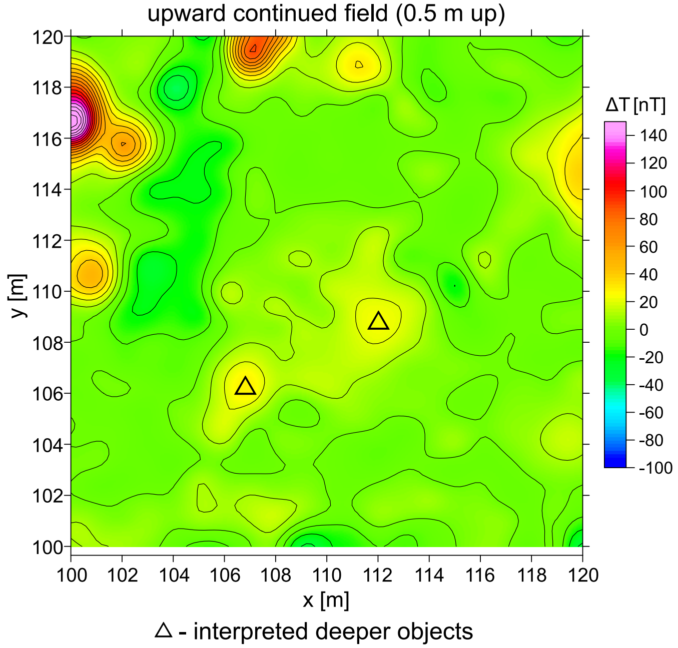


Fig. 4. Map of Upward Continued by 0.5 m anomalous magnetic induction field ΔT, from the second stage of the high-definition magnetic survey at the studied area. Triangles represent positions of local maxima of anomalies from interpreted deeper objects.

## 5. Analysis of stage 3 of the magnetic survey at Rohožník military training range

Having removed the top 1 metre of soil from a 15 × 15 m area in the centre of the site of interest, we conducted a third magnetic survey to the same specifications as before. Similarly, data were processed in the standard and already described way. The resulting anomalous magnetic induction ΔT field map is shown in Fig. 5. Marginal parts of the map were still influenced by shallow objects, which had been left in the ground, but the central part of the map showed well-defined manifestations of two isolated objects (marked by squares in Fig. 5). These two important anomalies were now clean of interference and from the resultant high signal-to-noise ratio, could be reliably interpreted by means of the two techniques that we have described. Figure 6 shows an XZ cross-section of the site showing the actual depths of all objects excavated. Also shown, are the calculated depths

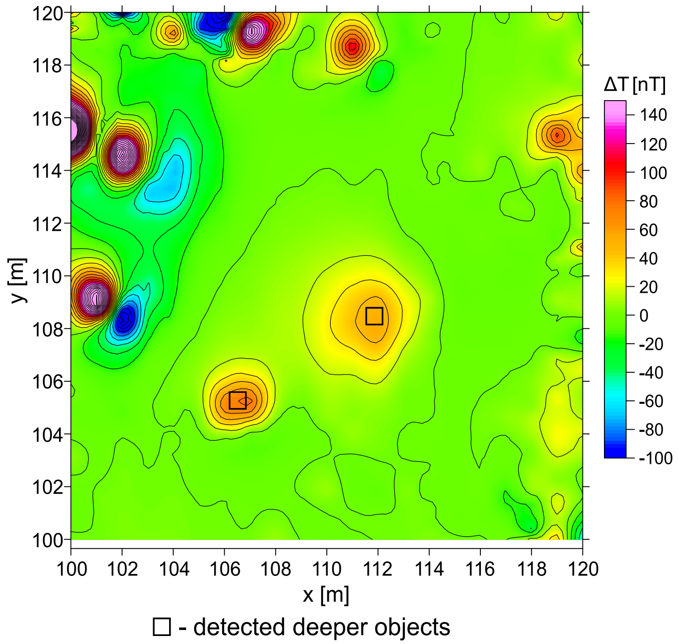


Fig. 5. Map of anomalous magnetic induction field ΔT, acquired during the third stage of high-definition magnetic survey at the studied area. Squares represent positions of local maxima of anomalies from interpreted deeper objects.

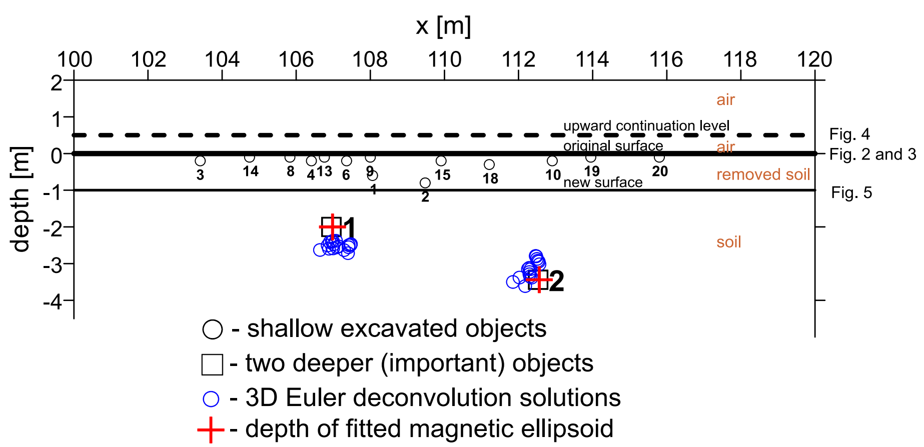


Fig. 6. Depths of all excavated objects presented in an XZ-section, together with the estimated depth solutions for the two important deeper objects.

of the two deep source items including the Mk-82 bomb of particular interest. The results of the depth estimations from the modelling approach have perfectly fitted the depth of both objects, with errors less than ±5%. The estimated depth of the first object was 1.0 m below the new surface, the second one was deeper – its depth was calculated to be 2.5 m. The results of the Euler deconvolution method were a little less accurate. In the case of object no. 1, it gave an over-estimate of the depth, a bit too deep and in the case of the object no. 2 little too shallow. These errors in the Euler depth estimation were within ±10–15% of the confirmed depths of the objects.

The first excavated deep object was found to be an aerial, non-explosive practise bomb with concrete filling from the producer Škoda (Fig. 7). This practise bomb has been widely used at this range over the last decades. However, it was a little surprising for the EOD technicians that it had penetrated to such a relatively large depth (2 m below the original surface). And the second deeper object was the unexploded Mk-82 aerial bomb that was the subject of this interesting project. It was found to have penetrated

Fig. 7. First of the deeper objects excavated (anomaly no. 2). It is a non-explosive test bomb with concrete filling from the producer Škoda. The length of the bomb was 1,200 mm, and its diameter 200 mm. Photo: R. Pašteka.

3.5 m below the original ground surface, a penetration depth not unexpected from this type of ordnance. Both deeper objects were found in horizontal positions – so the determination of their depths was quite explicit. The calculated depth of the object was identical with the depth of its centre. Excavation of this second object was a quite dangerous operation, so only EOD technicians could be present during this final stage of the project (Fig. 8) and geophysicists had to leave the place due to safety reasons. Unfortunately, due to some technical problems, a photo of the excavated bomb was not taken, and it had to be exploded as soon as possible. But the main object of interest was found and destroyed.

Fig. 8. The excavation of the second deeper object (the Mk-82 aerial bomb). A photograph of the excavated bomb itself could not be taken because of safety reasons. Photo: J. Jaráb (with courtesy).

## 6. Conclusions

In this contribution we have described the results of one rather unique case-study, which was performed in collaboration between geophysicists and explosive ordnance disposal technicians at the Rohožník military training range in SW Slovakia. The aim of this study was to localize one deeply penetrated unexploded ordnance object, an aerial Mk-82 bomb by means of high-definition magnetometry. The measurements were performed in three stages – with the aim to detect the shallow disturbing objects first and then remove them physically from the searched area. We have named this procedure "real magnetic stripping", because the source objects were really removed from the studied site between magnetic surveys, together with 1 m thick layer of the surface soil. During the detection and excavation of the searched objects, two quantitative interpretation methods were used – namely optimising modelling of source body first by a dipole and then an ellipsoid, and 3D Euler deconvolution method. Both methods yielded applicable outputs, but the former one gave much more accurate, stable and reliable results. In the case of the well-shaped, interference-free and adequately separated anomalies, acquired during the third stage of survey, the error in depth estimation by means of the modelling method was less than ±5%, while in the case of the Euler deconvolution method it was ±10–15%. In the case of the interpretation of more noisy and disturbed data (acquired during the first stage of survey) these errors were higher, namely ±50% for the modelling method and ±100% for the Euler deconvolution method. We repeat here the fact that in UXO survey it is very important to obtain a good accuracy of the depth estimates. For the EOD technicians this is crucial for safety reasons as during the digging of the interpreted objects they can take particular precaution when approaching to the expected depth of the object.

One specific step of the qualitative interpretation we consider very interesting. This was the application of upward continuation (0.5 m) of the anomalous field, which was performed within the second stage of the survey by means of a standard routine in Fourier spectral domain. From the upward continued field data we were able to resolve the ambiguity between the response from a discrete, deep object and a distribution of near surface sources that combined to produce a similar response at the original survey elevation. This interpretation was confirmed during the third stage of the investigation.

Finally, the expected unexploded aerial bomb Mk-82 was unambiguously detected, and its position precisely located in the third stage of survey. It was subsequently excavated and destroyed. For the authors of this contribution, it is obvious that the "real magnetic stripping" approach taken to locate this target was relatively time consuming and may not be justified as a standard approach in UXO remediation. On the other hand, we demonstrated that this methodology delivered a very effective, reliable and therefore safe solution and we are convinced that it can be applied in difficult situations where safety remains the top priority.

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