Journal of Applied Geophysics 112 (2015) 242–248

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

A novel test ground for the equipment qualification of magnetic gradient sensors used for unexploded bomb detection

Robert Hiergeist [a,c,*], Rainer Ketzler [a], Hans Harcken [a], Joachim Lüdke [a], Martin Albrecht [a], Thomas Brand [b], Andreas Fischer [b]

[a] Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany
[b] SENSYS GmbH, Rabenfelde 5, 15526 Bad Saarow (Neu Golm), Germany
[c] Magnet-Physik Dr. Steingroever GmbH, Emil-Hoffmann-Straße 3, 50996 Köln, Germany

ARTICLE INFO

Article history:
Received 26 July 2014
Accepted 2 December 2014
Available online 10 December 2014

Keywords:
Unexploded bombs
Equivalent current shell
Solenoids
Multi-layer split coils
Field calculations
Elliptic integrals

ABSTRACT

Scanning of the ground level by magnetic gradient sensors (fluxgate sensors) is the primary detection technique for unexploded bombs (UXBs). In order to allow a classification of the test equipment (magnetic sensors and associated evaluation software) as well as training and examination of the skills of sensor operating teams we built up a test facility. In the first step to generate the stray magnetic fields of UXBs, we positioned solenoids of the same dimension as the simulated bombs under a test ground using the principle of the equivalent current shell. From numerical investigations it has been found, that for depths exceeding 1.2 m, the gradient field profiles of these solenoids and the gradient field profiles of small multi-layer split coils agree very well (far field regime). This was verified later experimentally: By positioning these movable small multi-layer split coils in tubes running diagonally underneath the test ground and controlling the current flowing through these coils, we were able to find a good agreement between calculated and experimental data of the gradiometer signal scans on the measurement plane for (i) tests of the signal resolution and (ii) tests of the relative spatial resolution of the gradient sensors.

1. Introduction

For the detection of unexploded bombs it is commonly used that the massive steel or iron shell of the bombs is magnetized (a) unintentionally during the fabrication process (remanent magnetization) and (b) as a consequence of the susceptibility of the steel or iron shell in the earth magnetic field (induced magnetization) (Billings, 2004; McFee et al., 1990). Using the stray magnetic field of the resulting magnetic moment, the position of the bomb in the ground may be found by scanning the ground level by one or more fluxgate gradient sensors. [For technical details concerning fluxgate magnetometers see for instance the papers of Nielsen et al. (1991) and Primdhal (1979).] This way, only the component of the stray magnetic field perpendicular to the ground level is measured, which is the primary detection technique for unexploded bombs [prior to other techniques like measurements by gradiometers and magnetometers in drilled holes (Wegener and Fleischmann, 1954; Zhang et al., 2007), measurements with multi-sensor 3-axis fluxgate magnetometers (Munschy et al., 2007) or measurements with total-field magnetometers (Munschy et al., 2007; Nelson and McDonald, 2001; Robertson, 1981; Zhang et al., 2007)]. For a survey see e.g. the paper of McFee et al. (1990). Electromagnetic induction methods are methods of choice for the detection of buried ordnance, lying in lower depth (see for instance Friedel et al., 2012). Combinations of several methods – like electromagnetic induction methods and arrays of total-field magnetometers – are also discussed in the literature (Nelson and McDonald, 2001). Up to now, for this procedure no direct trace to the standards of a national metrology laboratory has been established allowing the use of poor quality sensors. As a consequence of this lack of quality control in some cases unexploded bombs were not found. The aim of this paper is to overcome this flaw. In the literature, one can find several papers (see e.g. Billings, 2004; Butler, 2003; Friedel et al., 2012; McFee et al., 1990, 1994; Munschy et al., 2007; Pawlowski et al., 1995; Zhang et al., 2007) that describe how to use buried unexploded ordnance (UXO) below a test ground in order to check locating and identifying algorithms with experimental data. In contrast, in this paper we describe how we used precisely calibrated coils positioned below a test ground – instead of buried ferromagnetic objects, which have the disadvantage of an unchangeable position and an unchangeable magnetic moment – to simulate the stray magnetic fields of unexploded bombs in order to test the capabilities of sensor systems and to train and to rate the skills of bomb detection teams.

* Corresponding author at: Magnet-Physik Dr. Steingroever GmbH, Emil-Hoffmann-Straße 3, 50996 Köln, Germany. Tel.: +49 2236 3919 82.
E-mail address: robert.hiergeist@magnet-physik.de (R. Hiergeist).

http://dx.doi.org/10.1016/j.jappgeo.2014.12.003
0926-9851/

2. Evaluation of empirical data of different bomb types

The magnetic moment of the bombs varies from case to case. Due to the elongated shape of the steel or iron shell of the bombs and the high permeability of this material, the orientation of the direction of the magnetic moment is assumed to be in many cases almost parallel to its largest dimension. The orientation of the UXBs in the ground and therefore the direction of the magnetic moment can be arbitrary.

Therefore – in the first step – empirical data of the magnetic moment of three different, very common bomb types were analyzed and thereby the mean magnetic moment values of these bomb types were classified. The data of the mean magnetic moment of the different bomb types are shown in Table 1 (Fischer and Brand, 2010; Muckel, 2010). Because of the small data basis of smaller (50 kg) and bigger bombs (1000 kg) these two types of bombs were omitted in Table 1.

3. Preparation of solenoids

Based on these data, solenoids were prepared with dimensions in accordance with the size of the steel or iron shell of the bombs (cf. Fig. 1). Thereby, it was made sure, that the stray magnetic field of the bomb shell was in agreement with the field produced by the current carrying solenoid even in the near field regime [cf. paragraph 12.07 "Equivalent Current Shell", p. 427 in the book of Smythe (1950), which is strictly speaking only true for the case where (i) the bomb is homogeneously magnetized and (ii) the magnetization direction is parallel to the long axis of the bomb.] Fig. 1 shows such a solenoid with dimensions similar to that of the GP250 bomb type (cf. Table 1). Note that the GP250 bomb type is the bomb model with the smallest mean magnetic moment in Table 1 and therefore the most problematic type for the exploration.

4. Calculation of gradiometer signals

4.1. Calculation of the stray magnetic flux density of test coils by using elliptic integrals

The analytical solution for the calculation of the field distribution of a current carrying circular loop based on the elliptic integrals of the first and second kinds is described in detail elsewhere [cf. paragraph 7.10 "Field of Circular Loop", in the book of Smythe (1950), p. 270 f.]. We used this approach to numerically calculate the stray magnetic field of different coil types by summing up the field generated by the individual windings of the coils (Hiergeist et al., 2010; Rezzoug et al., 1992). By multiplying the stray magnetic field obtained by this approach for a given coil current I by μ_0 we get the stray magnetic flux density $\boldsymbol{B}(I)$.

4.2. Calculation of the magnetic flux density of test coils by using their asymptotic magnetic moment

According to the book of Jackson (1998, p. 186), [cf. as well Eq. (4) of Billings (2004) and Eq. (1) of Zhang et al. (2007)] we used the equation

$$\boldsymbol{B} = [\mu_0/4\pi] \cdot [3\boldsymbol{n_r}(\boldsymbol{n_r} \cdot \boldsymbol{m}) - \boldsymbol{m}]/|\boldsymbol{r}|^3 \quad (1)$$

in order to calculate the magnetic flux density of the coils for large distances of the sensors relative to the center of the coils. Here $\boldsymbol{r}$ is the distance of the center of the coil relative to the position of the sensor, $\boldsymbol{n_r}$ is the normal vector of $\boldsymbol{r}$, and $\boldsymbol{m}$ is the magnetic moment vector of the coil. The magnetic moment was determined from the asymptotic behavior of $\boldsymbol{B}$ calculated by using elliptic integrals (cf. Section 4.1) for large distances between the coil and the sensor.

Table 1
Data of different bomb types (US "AN-Series", General Purpose (GP) bombs).

Bomb type	Weight[a] kg	Length without tail unit[b] cm	Diameter[b] cm	Mean magnetic moment m[a] Am^2
GP250	125	91	28	7.2
GP500	250	114	36	20.2
GP1000	500	135	48	38.0

Data were taken from references [a]Fischer and Brand (2010) and [b]Muckel (2010).

It should be noticed here that Eq. (1) describes the far field behavior of $\boldsymbol{B}$ for our test coils (Billings, 2004; McFee et al., 1994; Zhang et al., 2007).

Fig. 2 shows the geometry used in order to calculate the z-component of the flux density perpendicular to the ground level.

By these two methods (Sections 4.1 and 4.2) we were calculating the part of the magnetic flux distribution perpendicular to the ground level B_z and in a second step, we were able to simulate gradiometer signals, which are just the difference of two B_z-values in different heights above the ground level.

Thus we are able to simulate the signals of different gradiometer types (i.e. for different gradiometer bases, which differ from gradiometer type to gradiometer type, and different distances of the center of the gradiometer to the ground level). For the sake of simplicity, we restricted us in this paper to one common type of gradiometer sensor with 0.65 m gradiometer basis distance and a distance of the center of the gradiometer to the ground level of 0.60 m. (In order to make sure that distance of the center of the gradiometer to the ground level is always 0.60 m, in our experiments the gradiometer was attached to a trailer.)

5. Positioning of coils below the test area

In order to position test coils below a test area, two tubes were buried. In Fig. 3 a model is presented, which shows the geometry of these two tubes running below the test ground. There is a tube with 370 mm bore with an inclination of 15.6° (indicated by line (a)) and a tube with a bore of 280 mm and an inclination of 10.2° (here shown as line (b)).

In order to position the test coils into these tubes rolls were mounted onto that coils. (Note the rolls mounted to the coil shown in Fig. 1.) Furthermore, these rolls prevent a rotation of the coil around its longitudinal axis during positioning and therefore a twisting of the connecting cable. The positions of the coils during the test runs were fixed by the use of stay ropes.

6. Comparison of experimental data with calculations for solenoids

In Fig. 4 a comparison of experimental gradiometer signal data and simulated data calculated by using elliptic integrals (Section 4.1) is shown. Technical data of the magnetic gradient sensors (vertical fluxgate gradiometers FGM650) and of the trailer configuration used for this and the following experiments (Magnetic Areal Survey System MAGNETO® MXPDA 5 channel magnetometer system) are described in detail elsewhere [see (Fischer and Brand, 2014a, 2014b), respectively].

As can be seen in Fig. 4 we get a good agreement of the simulated data with the experimental data despite the low values of the gradiometer signals which are in the range below 10 nT. In order to obtain these low values the coil of Fig. 1 was positioned in the 370 mm bore tube running below the test area as shown in Fig. 3 in a depth of 3.20 m below ground level. (The depth of 3.20 m is the largest accessible depth for this tube for the coil of Fig. 1.) It was driven by a current of $I = 0.459$ A which is asymptotically equal to a magnetic moment of $\boldsymbol{m} = 7.2$ Am^2 (i.e. the mean magnetic moment found for a GP250 bomb, the bomb type with the lowest mean magnetic moment in Table 1). Due to the dimensions of this test coil, the inclination of the coil axes is identical to the inclination angle of the 370 mm tube, i.e. $\theta = -15.6°$. The label of the x-axis of Fig. 4 "Lateral Sensor Position" indicates that the sensor is moved in the direction of the coil axes (i.e. in the direction where the azimuth angle $\phi = 0°$). The good agreement between experimental and calculated data in Fig. 4 also reveals the low magnetic background of the soil in the case of our test ground. [The