MNPQ-Project: A test ground for the characterization and qualification of magnetic gradient sensors which are used for the detection of unexploded bombs

Unexploded bombs (UXBs) are consisting of massive steel or iron shells, which are magnetized (a) unintentionally during the fabrication process and/or (b) due to the susceptibility of this steel or iron shell in the earth magnetic field. For the detection of UXBs, the stray magnetic field of the resulting magnetic moment of the bombs is commonly used: the position of the bomb below the ground level may be found by exploration with one or more fluxgate gradient sensors. In this way, only the component of the stray magnetic field caused by the magnetized UXBs is detected, which is perpendicular to the ground level (cf. Ref. [1]).

Up to now any gradient sensor – as well low quality devices - could be used for UXB prospection. As a result, in some cases UXBs were overlooked.

Therefore, in the framework of the MNPQ-project presented here, a cooperation between the SENSYS GmbH, Bad Saarow und the PTB-Braunschweig has been launched, with the aim to establish a quality control and classification of the magnetic gradient sensors and to obtain a direct trace to the standards of a national metrology laboratory like the PTB. Furthermore, training and an examination of the skills of the sensors operating personnel should be enabled.

As a test structure, two tubes running diagonally underneath a test ground of the SENSYS GmbH, Bad Saarow, is used. Fig. 1 shows the geometry of these two tubes. There is a tube with 370mm bore and an inclination of 15.6° (red line) and a tube with a 280mm bore and an inclination of 10.2° (gray line).

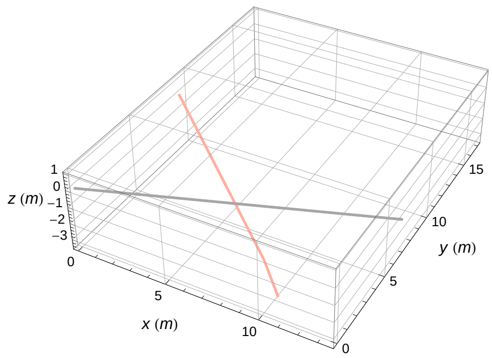

Fig. 1 Two tubes (gray and red line) running below the SENSYS-test area

By numerical simulations, it could be shown, that for depth exceeding 1.2m below ground level, a far field regime of the stray magnetic field distribution for UXBs of the type GP250 („General Purpose“-bombs with a weight of approximately 125 kg) remains. This far field regime allows the calculation of the stray magnetic flux distribution **B** of the UXBs providing the magnetic moment **m** according to (cf. Ref. [2])

$$\mathbf{B} = [\mu_0/(4\pi)]\,[3\mathbf{n}_r(\mathbf{n}_r\cdot\mathbf{m}) - \mathbf{m}]/\cdot|\mathbf{r}|^3 \quad . \qquad (1)$$

(Here $\mathbf{n}_r$ denotes the unit vector in the direction of the distance vector **r** between the magnetic moment **m** and the position above the ground level where the stray magnetic flux **B** is detected.) Furthermore, this far field regime allows the simulation of the stray magnetic flux of the UXBs by coil systems, which are significantly smaller than the here considered bombs of the GP250-type. For the simulation of the stray magnetic fields of UXBs, the two in Fig. 2 shown coils were used.

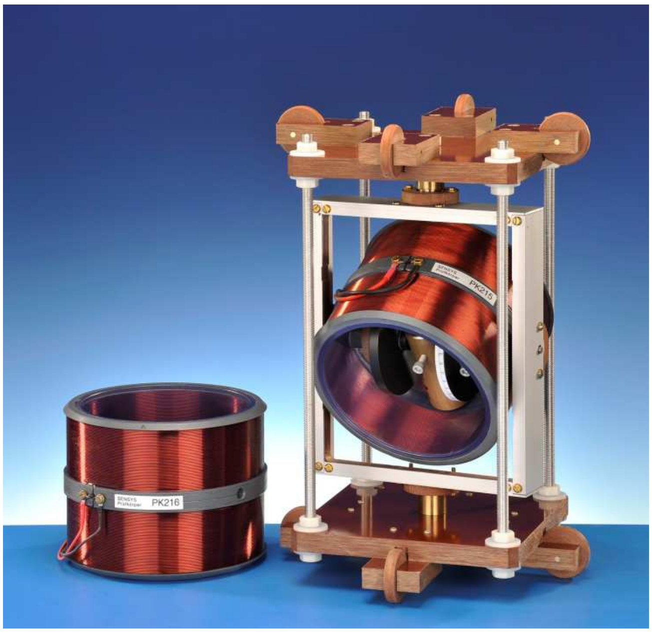

Fig. 2 Picture of two identical rotatable coils PK215 (here on the right hand side mounted within a trolley stand for the positioning of the coil in the tubes running below the SENSYS-test area) and PK216 (on the left hand side without frame) for the simulation of the stray magnetic fields of UXBs.

For both coils trolley stands were built, allowing their positioning in the tubes shown in Fig. 1 by the use of stay ropes. By varying the length of the stay ropes, the depth of the coils below the ground level can be altered. A gimbal, mounted within the trolley stand, allows by the use of a lead weight the perpetuation of the polar angle of the coil axis with respect to the ground area (cf. Fig. 2 right hand side).
The magnetic moment of these two coils with respect to the coil current was measured according to the method described in Ref. [3] by reversing the current direction in the coils several times. This way, for both coils, within the measurement uncertainty, the same specific magnetic moment of

$$m/I = (13.173 \pm 0.065)\ \mathrm{Am^2/A} \qquad (2)$$

has been found, which demonstrates the high quality of these two coils.

For the test structures, which were developed within our project, we selected from the various possible geometrical formations for the rotatable coils those, with the coil axis direction perpendicular to the ground level (i.e. the geometries with the coil axis parallel to the z-axis).
By the restriction to these geometries, a significant simplification of the test structures is achieved, for the classification of the gradiometer signals (by use of one of the two test coils), as well as for the classification of the spatial resolution (by simultaneous use of both of the test coils of Fig. 2), as is discussed in the following.

A. Classification of gradient fields: For the classification of gradient fields one of the test coils of Fig. 2 is positioned in one of the tubes running below the SENSYS test ground with the coil axis perpendicular to the ground level. The characteristic feature of these configurations is the rotational symmetry of the resulting gradiometer signal. Fig. 3 shows a profile running though the maximum of such a gradiometer signal (calculated according to Equ. (1)). Here, for a given depth of the coil below the ground level, the coil current was adjusted so that (for a gradiometer basis distance of 0.65m and a distance of the center of the gradiometers to the ground level of 0.60m) in the maximum of the gradiometer signal a value of exactly 32nT has been achieved (full line at the zero sensor-x-position). As can be seen in Fig. 3, we obtained a good agreement between the calculated data and experimental data of an exploration with fluxgate gradient sensors on the test ground.

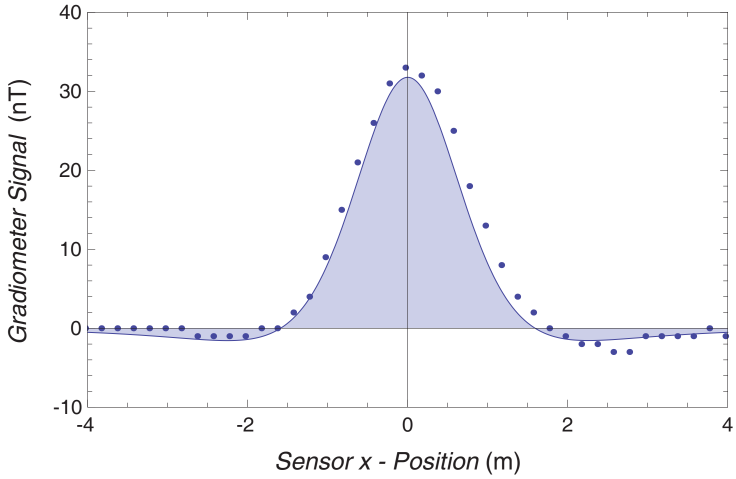

Fig. 3 Profile of the gradient signal (full line) calculated by use of Equ. (1) for a magnetic moment of $1.185Am^2$ in a depth of the magnetic moment below ground level of 1.39m. The discrete experimental data points plotted above were selected from an exploration on the test ground with fluxgate gradient sensors by use of the coil PK215 shown in Fig. 2.

Furthermore, due to the good agreement between experimental and calculated gradiometer data shown in Fig. 3, we can conclude, that this setup allows the compilation of grading tables. In these tables a classification information (i.e. a mark) is assigned to that maximum value of the gradiometer signal profile, which is barely detected by the equipment under test.

B. Classification of the spatial resolution: First of all, numerical calculations concerning the spatial resolution of two magnetic moments were made, which were oriented in parallel and in perpendicular with regard to the ground level. Equ. (1) was used for the calculations of the gradiometer signals. The two magnetic moments were assumed to be positioned in both tubes shown in Fig. 1. Due to these calculations, it was found, that for small distances between both magnetic moments - as a consequence of the positive superposition of the resulting gradiometer signals - only one maximum of the gradiometer signals on the ground level appeared. Two distinguishable maxima of the gradiometer signals on the ground level were obtained in the numerical simulations, when sufficient distances between the two coils were assumed. Only for the latter cases a classification of the spatial resolution is reasonable.

A profile of the gradiometer signal for the case with two distinguishable maxima is shown in Fig. 4. In this figure, the profile of the gradiometer signal running on a straight line through both maxima is shown.

Here, the currents for both coils and therefore the according magnetic moments (cf. the Equs. (1) and (2)) – were fixed, so that by considering the positions of the two coils in the tubes below the SENSYS test area, both maxima (indicated by the two green points in Fig. 4) had equal height.

Furthermore, the free choice of the coil currents in both coils allows a determination of the gradiometer signal difference between the maxima (green points in Fig. 4) and the saddle point minimum (dark red point in Fig. 4) (Note here, that the restriction to geometries with the coil axes parallel to the z-axis ensures, that the saddle point minimum lies exactly on the straight line between the two local maxima of the gradiometer signal.) As can be seen in Fig. 4, also for the geometry considered here with the simultaneous use of two coils, we find a good agreement between calculated data and data obtained by prospection on the test area.

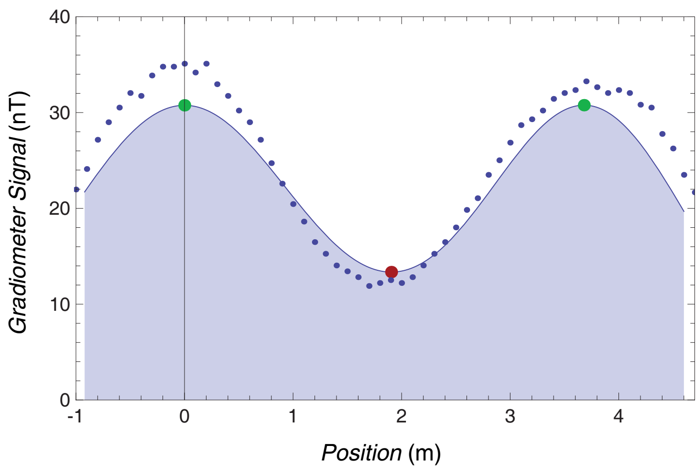

Fig. 4 comparison of the profiles of the gradiometer signal calculated according to the data of the magnetic moment of both coils shown in Fig. 2 (solid line) on the straight line between the two maxima (indicated by the two green points) with experimental data points (blue discrete points). The saddle point minimum of the calculated gradiometer signal between both maxima is indicated by the dark red dot. (The distance of the two coils under the test area is for the case considered here 3.69 m. The difference between the gradiometer signal in the two maxima and the saddle point minimum is according to our calculations 17.42 nT.)

Similar as in the case *A. Classification of gradient fields* – we use for the case *B. Classification of the spatial resolution* the good agreement of the experimental and calculated gradiometer data as can be seen in Fig. 4. This good agreement allows the compilation of a grading table where a mark is assigned to that difference ΔG between the maximum value of the gradiometer signal profile and the gradiometer signal at the saddle point minimum, which is barely detected by the equipment under test.

Summary

We can conclude that the coil systems built within the scope of the MNPQ- project presented here, which were positioned in tubes below a test ground, are feasible to simulate the magnetic signatures of unexploded bombs. It has been found, that the testing procedures presented above allow an equipment qualification of magnetic gradient sensors as well as a training and an examination of the skills of the sensors operating personnel. The discrepancies by misleading measurement data found in past should be reduced to a minimum by those new qualification procedures. Furthermore, the use of the coil systems provides a trace to the standards of the PTB.

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[1] http://www.sensys.de/index.php/104.html
[2] John David Jackson, „5.6 Magnetic fields of a local current distribution, magnetic moment” in Classical Electrodynamics, 3rd. ed., New York: John Wiley & Sons, 1998, Equ. (5.56), p. 186.
[3] DIN EN 60404-14 (2003-02) “Magnetic Materials - Part 14: Methods Of Measurement Of The Magnetic Dipole Moment Of A Ferromagnetic Material Specimen By The Withdrawal Or Rotation Method)“.