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Advanced Geophysical Classification of WWII-era Unexploded Bombs Using Borehole Electromagnetics

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FEATURE

ADVANCED GEOPHYSICAL CLASSIFICATION OF WWII-ERA UNEXPLODED BOMBS USING BOREHOLE ELECTROMAGNETICS

by Laurens Beran, Ph.D., and Stephen Billings, Ph.D. [Black Tusk Geophysics, Inc.]

The legacy of World War II-era unexploded bombs (UXB) is an ongoing public safety hazard throughout Europe, and especially in Germany. Large, air-dropped bombs that are a legacy of Allied bombing campaigns are discovered on a weekly basis in Germany, requiring evacuations and disposal efforts costing hundreds of thousands of Euros in some instances.

This article presents recent work done by Black Tusk Geophysics using advanced geophysical classification (AGC) to reliably identify hazardous ordnance at urban sites in Germany. After briefly describing electromagnetic (EM) sensors and data processing required for AGC, this article will discuss survey and design considerations for characterization of large, deep UXBs in urban environments.

Advanced Geophysical Classification

AGC combines geophysical sensors designed for detection and characterization of metallic targets with physical modelling of digital data to extract an intrinsic fingerprint for each target. This approach allows for reliable identification of intact ordnance and rejection of metallic clutter that would otherwise be excavated using conventional clearance methods (e.g., analog detection). Through U.S. Government-funded research and development programs, AGC technology has now matured to the point that it is mandated for munitions response work in the United States, and contractors must obtain International Organization for Standardization (ISO) accreditation to perform AGC work.[1]

AGC EM sensors rely on the same pulse-induction principles used in conventional metal detectors.[2] A time-varying primary magnetic field is transmitted into the earth and induces currents in electrically conductive targets. These induced currents in turn radiate a secondary magnetic field that is measured by receivers at the surface. In order to support target classification, advanced EM sensors employ three or more transmitters to obtain multiple looks at a target, and multiple receivers measure all components (i.e., x, y, and z) of the secondary fields induced by each transmitter.

These digital data are subsequently processed to recover a location, orientation, and depth for each detected target. Additionally, intrinsic target parameters, or **polarizabilities,** estimated from the data provide a target fingerprint and can be matched against a library of polarizabilities for ordnance. Polarizabilities also provide an indication of a target's size, shape, and composition (i.e., magnetic or non-magnetic metal), and can be used to identify unexpected ordnance that may not be included in a library.

Advanced Geophysical Classification for Large and Deep UXB

In the context of the German UXB problem, there are two main challenges to the application of AGC. First, ordnance can be significantly deeper than is typically encountered at North American military ranges. Whereas mortars and projectiles are usually restricted to the top 2 m below ground surface, larger, air-dropped bombs of 250 lbs or greater are regularly encountered at depths up to 10 m. This is well outside the detection range of typical AGC sensors. Second, most urban sites have nearby infrastructure with a significant amount of metal (e.g., rebar, piping, etc.) that produces a strong EM response and obscures the signal from targets of interest. Images 1 through 4 (next page) show examples of urban locations where we have carried out borehole AGC surveys in Germany.

To overcome these challenges to AGC in Germany, we use a high-current transmitter and large transmitter loops to illuminate targets at depth. This produces a stronger field at depth than is possible with typical AGC sensors, which have transmitter loop sizes on the order of 1 m. Loops are

Images 1–4 (left). Examples of borehole EM surveys carried out at urban sites in Germany (blue PVC tubes are borehole casings). The red cable, most evident in Image 2, shows the transmitter cable, and wooden stakes are used to position loop corners. The yellow table visible in Image 3 is used to orient and lock the grey vertical shaft, which has the fluxgate magnetometer at its downhole end.
All graphics courtesy of Boskalis Hirdes GmbH.

ideally arranged to obtain illumination of a deep target from multiple directions. This is achieved with a rectangular transmitter loop that generates a vertical field, and figure-eight loops that generate horizontal fields (Figure 1, next page).

The field team collects measurements of the secondary field induced in a buried target using a fluxgate magnetometer that is deployed down boreholes. Fluxgate receiver measurements collected at depth significantly increase the amplitude of the measured target response and attenuate the background response due to infrastructure. This allows classification of targets that cannot be detected by typical AGC sensors deployed at the surface.

Typically, a prospective target is initially detected with another geophysical sensor deployed at the surface (e.g., ground penetrating radar or magnetics). Boreholes are subsequently drilled and cased with PVC tubing at approximately 2 m distance from the target. Fluxgate measurements are made at 0.5 m intervals in each borehole, ideally at depths ranging down to 2 m below the expected target. The fluxgate magnetometer measures three components of the magnetic field induced in a target. This receiver also provides a much longer measurement window (about 50 ms) than the loop receivers usually used for AGC applications (typically extending out to about 25 ms). This longer window allows for improved target classification in the presence of the background infrastructure response, as well as rejection of fast-decaying clutter. The fluxgate magnetometer data does, however, require removal of the earth's ambient magnetic field as well as careful control of sensor orientation during data acquisition.

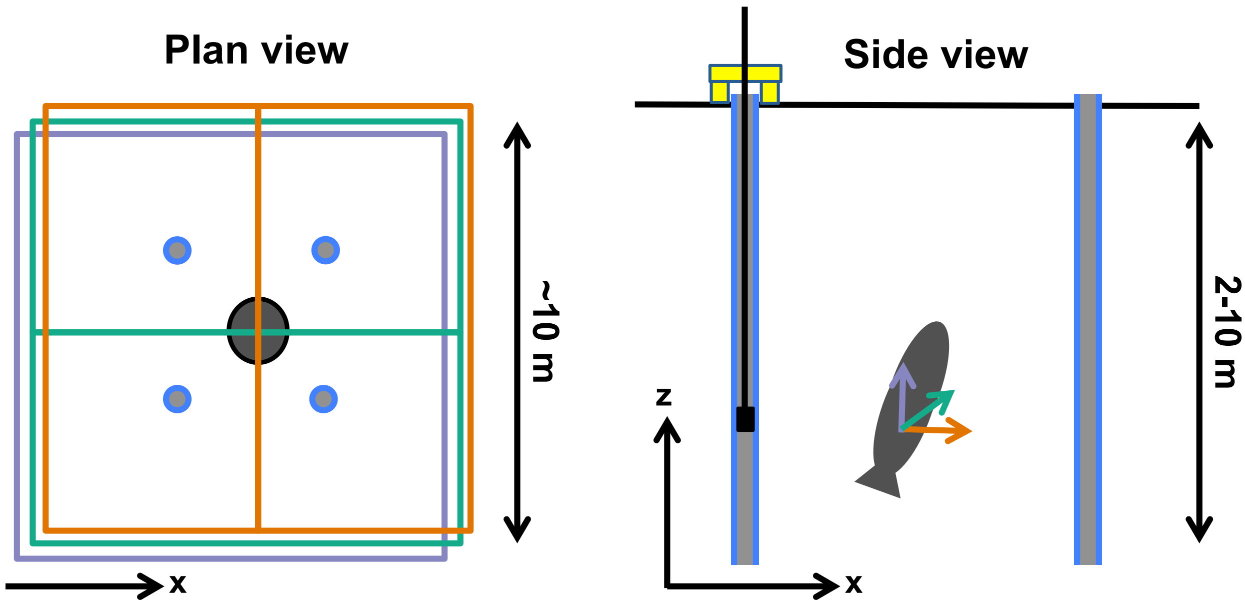

Figure 1 (above). Schematic of borehole EM survey. On the left, the plan view shows transmitter loops that generate primary magnetic fields directed in x, y, and z directions at the center of the survey (red, green, and blue lines, respectively). Loop offsets are for visualization; in practice loop corners coincide. Blue circles show typical borehole geometry with boreholes offset approximately 2 m from the center of the survey. On the right, the side view shows primary magnetic fields at the location of a buried target, boreholes, and receiver apparatus (yellow table and downhole magnetometer in left borehole).

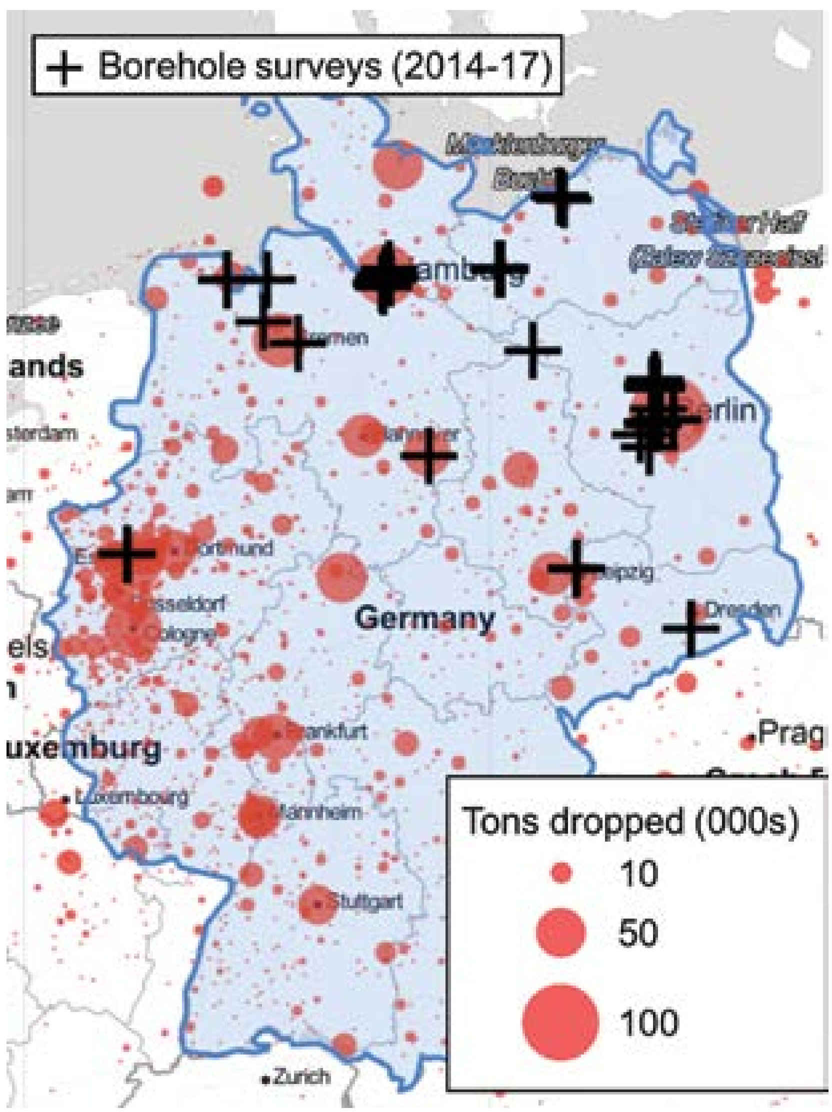

Figure 2 (right). Historical map of Allied bombing from 1939 to 1945, generated using Theater History of Operations data.[3] Approximately 150 locations in northern Germany surveyed using borehole electromagnetics are also shown, with a large concentration in Oranienburg, just north of Berlin.

Borehole survey in Oranienburg, Germany.

A 500 lb U.S. General Purpose (GP) bomb subsequently excavated at this site. The target was reflected off of bedrock, resulting in a nose-up orientation that prevented triggering of the delayed-action fuse.

UXB Classification in Oranienburg, Germany

Since 2014, Black Tusk Geophysics and partners have carried out more than 100 borehole surveys to characterize buried targets in Germany (Figure 2). The work has been concentrated in and around Berlin and in particular in the northern suburb of Oranienburg. This town underwent heavy aerial bombardment from 1944 to 1945. Oranienburg was targeted for its military and logistical importance, and because it was the site of uranium processing for the German nuclear research program. On 15 March 1945, American B-17 bombers struck the town in order to prevent the advancing Soviets from seizing German nuclear facilities.

During multiple air raids on Oranienburg, Allied bombers dropped ordnance equipped with delayed action fuses designed to trigger detonation hours or days after impact. The fuses were designed to trigger if the bomb rested in a

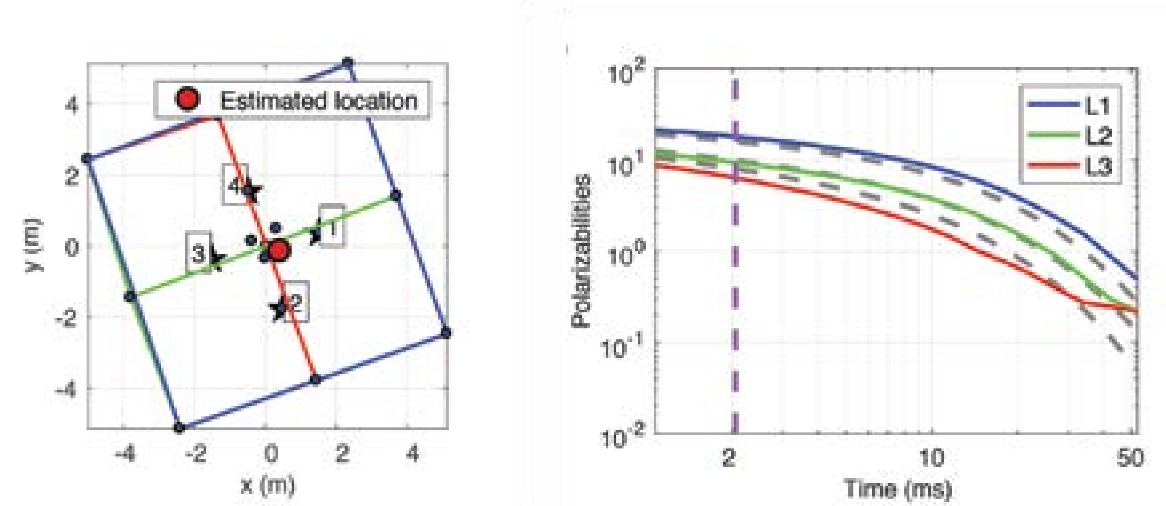

Figure 3. Borehole EM data and analysis for survey shown in Images 5, 6 and, 7. Left: Borehole survey geometry with solid lines indicate transmitters, and numbered stars indicate measured boreholes. The red marker indicates estimated target location; the estimated depth is 3.9 m. Right: Estimated polarizabilities (solid lines) and reference polarizabilities for 500 lb U.S. GP bomb (dashed lines). The vertical dashed line indicates 2 ms time channel for data shown in Figure 4.

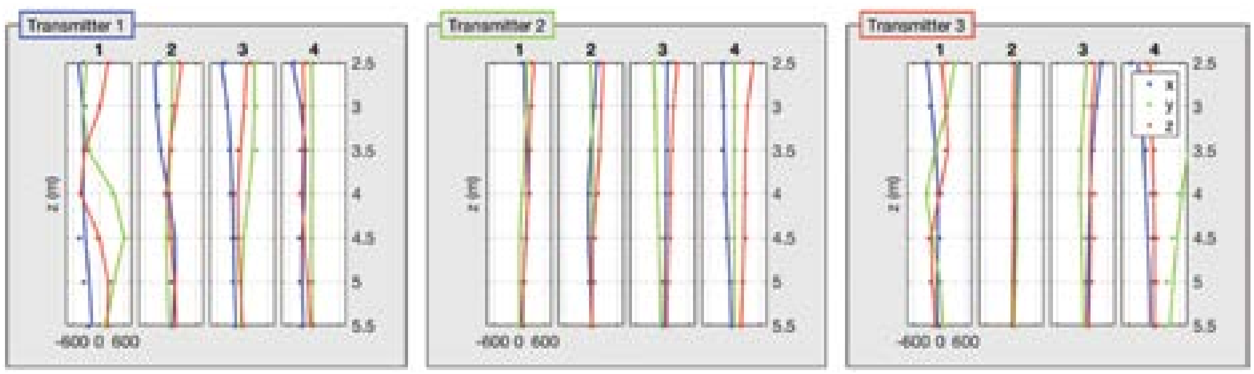

Figure 4. Data collected in the four boreholes for the survey in Figure 3. Axis titles indicate borehole numbers. Observed x, y, and z-component data (dots) were measured at 0.5 m intervals between 2.5 and 5.5 m below the ground surface. Data are in units of picoTesla/Ampere. A strong anomaly is apparent in the data, particularly in borehole 1. Predicted data obtained by fitting a model to the observed data are shown as solid lines. The model predicts a target at 4 m depth with location and polarizabilities shown in Figure 3.

nose-down orientation. However, many delayed action bombs in Oranienburg ended up in nose-up orientations after they encountered bedrock, and authorities estimate that there are hundreds of unexploded bombs still present in the town.[4] The delayed action fuses are highly unstable and can easily be triggered if a bomb is disturbed.

Images 5, 6 and 7 (previous page) show photos of a borehole EM survey and subsequent target excavation carried out in a pedestrian area in Oranienburg in 2017. Borehole data collected with this survey are shown in Figures 3 and 4. Our AGC analysis found that this anomaly was a good match to a 500 lb U.S. bomb, with slow-decaying polarizabilities that are indicative of intact ordnance.

While the previous example is a clear-cut case of an intact UXB, the majority of targets (about 80 percent) surveyed using borehole EM are eliminated as potential UXBs on the basis of Black Tusk Geophysics' AGC analysis. Low amplitude and/or fast-decaying polarizabilities are diagnostic of smaller items and allow for unambiguous target classification and a reduction in unnecessary excavations. This is in contrast with other geophysical methods used to detect deep UXBs. In particular, while borehole magnetometry can reliably detect ferrous (e.g., steel) targets, characterization with magnetics data can be ambiguous because the parameters extracted from magnetics data are not uniquely related to target size.[5]

Finally, Images 8 and 9 (next page) highlight quality control (QC) of AGC using borehole EM. In the context of conventional AGC surveys using EM sensors deployed at the surface, blind seeding of standardized test items is used by regulators to verify that classification processing carried out by a contractor will identify all targets of interest. Given the size and depth of UXBs encountered in borehole surveys,

Images 8 and 9. Data collection at a borehole test pit. A 3 m deep test pit is used to collect measurements of ordnance that are then added to a reference library of target polarizabilities. The test pit is also used to collect QC measurements that verify classification processing.

blind seeding at field sites is impractical. We instead use data collected at a test site to verify that classification processing works for known items; groundtruth is withheld from the data analyst for these data sets. In addition, we have augmented our polarizability reference library by collecting high-quality measurements with inert ordnance in the test pit.

Conclusion

Black Tusk Geophysics have extended AGC techniques developed for identification of small, near-surface munitions to the problem of large, deep UXBs in urban environments. Using large transmitter loops at the surface and receivers deployed down boreholes, this technology can minimize response from infrastructure and characterize targets that cannot be detected with EM sensors operating on the surface. AGC processing of borehole data provides improved identification of UXBs relative to other geophysical methods (magnetics or radar) and reduces unnecessary excavations of metallic clutter. Ongoing work is investigating the use of this technology for characterization of UXBs in the presence of magnetic soils in Southeast Asia.

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Dr. Laurens Beran is a senior geophysicist with Black Tusk Geophysics in Vancouver, Canada. He specializes in development and application of algorithms for classification of unexploded ordnance (UXO). Dr. Beran has served as the principal investigator of Strategic Environmental Research and Development Program (SERDP) projects MR-2226 and MR-1629. His current work focuses on detection and classification of deep UXO and underwater UXO. Dr. Beran completed his master's and doctoral degrees in geophysics at the University of British Columbia.

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Dr. Stephen Billings has over 20 years' experience working with geophysical sensor data, including 17 years where he has concentrated on improving methods for detection and characterization of UXO. He is an adjunct professor in Earth and Ocean Sciences at the University of British Columbia. He has also been a principal investigator on 10 completed SERDP-ESTCP munitions response projects, ranging from developing and testing classification strategies for magnetic and electromagnetic sensors to developing and certifying new sensor systems. Dr. Billings is based in Brisbane, Australia.

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1. Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP). “Munitions Response.” Accessed 11 April 2018. https://bit.ly/2qnj9zP.
2. Beran, L., B.C. Zelt, and S. D. Billings. “Detecting and Classifying UXO.” Journal of ERW and Mine Action 17.1 (2013): 57-62. Accessed 11 April 2018. https://bit.ly/2qoIF7Q.
3. “Theater History of Operations (THOR) Data: World War II.” Data.world. Accessed 11 April 2018. https://bit.ly/2EEghmu.
4. Holm, C. “Germany's WWII Duds Get Deadlier.” Spiegel Online (2012). Accessed 11 April 2018. https://bit.ly/2EE4O6r.
5. Billings S. D. Discrimination and Classification of Buried Unexploded Ordnance using Magnetometry. IEEE Transactions on Geoscience and Remote Sensing 42 (2004) 1241-1251.