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Magnetic Area Surveys for UXO Detection – Scalar or Vectorial Magnetometers?

Introduction

Magnetic area surveys are used in a number of different fields to map and detect anomalies in the Earth magnetic field. These applications range from resource exploration, engineering geophysics, and utility mapping to unexploded ordnance (UXO) detection.

There are many different types of magnetometers that can be applied for these tasks. Common types include fluxgate magnetometers, resonance magnetometers and SQUIDS (Superconducting Quantum Interference Devices). All types of magnetometers have different principles of operation, different sensitivities, and different advantages and disadvantages [Ripka 2001, Clarke 2006, Militzer 1981, Breiner 1973].

The magnetometers mentioned above are distinguished in two different classes, namely scalar magnetometers that measure only the total magnitude of the Earth magnetic field independent of its direction, and vectorial magnetometers that measure one or more components of the Earth magnetic field in a particular direction.

For UXO detection in Europe, mainly fluxgate vertical gradiometers are used, while in the USA and Canada, scalar resonance magnetometers are preferred for the same task. The purpose of this paper is to discuss whether one of the two classes of magnetometers should be preferred for purposes of UXO detection or whether one of the two should be preferred for this task.

Area Surveys for UXO Detection

For area surveys in UXO detection, two types of magnetometers are typically used, namely fluxgate vertical gradiometers (Foerster probes) and Cesium vapor magnetometers. The former belong to the group of vectorial magnetometers, the latter belong to the group of scalar resonance magnetometers.

Fluxgate vertical gradiometers (Foerster probes) consist of two magnetic fluxgate sensors that are aligned with high precision along a common axis at a fixed distance (sensor separation). Older magnetometers of this type have sensors that are mechanically aligned, newer types use the tension band technology where the sensors are permanently aligned and need no re-adjustment in regular intervals. The fluxgate vertical gradiometers applied in UXO detection typically have a sensitivity of 0.1 nT and a measurement range of ±10.000 nT. For measurements, fluxgate vertical gradiometers are guided over the area of investigation vertical to the surface. For each measurement point, the fluxgate vertical gradiometers measure the difference in the local magnetic field between the lower and the upper sensor. Their main advantage is that they require no base station for correcting data of the magnetic survey as only the difference of the magnetic field at any give location is measured. Thus, variations of the magnetic field over time are eliminated because they affect both sensors similarly. Other advantages include their long-term stability and reliability (sturdiness), and the fact that these magnetometers do not influence each other even if they are applied in sensor arrays with small sensor separations (0.25 m or less between two sensors). Their main disadvantage is that deviations from the vertical during the survey will result in small noise amplitudes. This, however, can be solved through the array design. Another disadvantage is that fluxgate vertical gradiometers are perfect to apply in Northern and Southern latitudes, where the vertical component of the Earth magnetic field is dominating, but less suitable in latitudes around the equator where horizontal components of the Earth magnetic field are dominating.

Scalar resonance magnetometers, the most common type used for UXO detection being Cesium vapor magnetometers, typically have a sensitivity of 0.01 nT, one order or magnitude higher that of fluxgate vertical gradiometers. Resonance magnetometers typically consist of single magnetic sensors that may be applied in different setups, either as single sensors or as gradiometers consisting of two or more sensors taking measurements for the same point. The sensors of scalar resonance magnetometers measure the total magnitude of the local magnetic field at a measurement point. Only if more than one sensor is applied, time variations of the magnetic field can be eliminated. The main advantage of resonance magnetometers is that they have a higher sensitivity than fluxgate vertical gradiometers and that the measurement is independent of the orientation of the sensor. Their main disadvantage is that while they measure the amplitude of the total magnetic field rather than one component, all directional information that is paramount for object calculation is lost.

Which resolution is necessary for UXO surveys?

The main question is which resolution of the magnetic sensors is necessary for magnetic surveys for UXO detection. In order to answer this question, it is necessary to consider the typical magnetic anomalies of UXO and similar objects as well as the sensor-independent noise typically experienced during these surveys.

UXO and other iron and steel objects buried in the subsurface or lost underwater produce local anomalies in the Earth magnetic field. Depending on their size and magnetization, the signatures produced by these objects vary in size (area covered by the signature) and amplitude (magnitude of the disturbance of the Earth magnetic field). For UXO, anomalous signatures cover between a few square decimetres for 2-cm-rounds and more than 100 square meters for unexploded bombs (UXB). The amplitude of the signatures will range between single Nanoteslas for small objects and also large objects that are far away from the sensor, and several hundred of thousand Nanoteslas for large objects and objects that are close to the sensor.

However, magnetometers used for UXO surveys do not only measure the pure signatures of UXO and other ferrous objects, but also ubiquitous noise. Noise includes all signals measured by a magnetometer that does not originate from the target object, but from other sources. Noise in magnetic surveys includes time variations of the Earth magnetic field, magnetic structures and small objects of geologic origin, moving objects made from ferrous materials (in particular vehicles of all kinds), alternating and DC fields produced by electric sources, and instrument noise. Depending on the location of the survey, these types of noise may range from 0.1 nT for low-noise environments (e.g. in offshore measurements) up to several hundred Nanoteslas in urban areas, thus making magnetic surveys for UXO virtually impossible.

The most important source of noise in magnetic surveys for UXO detection, however, is the so-called movement noise. It is produced when a magnetic sensor is moved in the magnetic field, in particular when changing its distance from the surface being investigated. This noise typically ranges from 0.5 nT to 1.5 nT in all magnetic area surveys independent of the sensor used. The amplitude of movement noise largely depends on the stability of the platform used for guiding the sensors over the area of investigation. When considering this with respect to the choice of sensors for a magnetic area survey for UXO detection, it becomes clear that there is no need to use resonance magnetometers with a resolution of 0.01 nT as these would only resolve the noise with higher precision but would not result in improved survey results. The resolution of fluxgate vertical gradiometers of 0.1 nT is therefore sufficient to resolve UXO signatures with an amplitude of 3 nT or more in a survey with a noise level of 0.5 nT or 1.5 nT.

When discussing differences between scalar and vectorial magnetometers, the fact that the magnetic field decreases with the fourth power of the distance between the sensor and the magnetometer for vectorial magnetometers but only with the third power for scalar magnetometers, is often cited. Although this is true, it does not have a significant effect for larger objects even at higher distances between the magnetometer and the object when considering noise as discussed above. The measurement is based on the passive measurement of disturbances in the Earth's magnetic field caused by ferromagnetic objects on the surface and in the subsurface. Using two single-axis fluxgate sensors at a set distance in vertical alignment, only the vertical component of the disturbed magnetic field is measured. Because the vertical component of the Earth Magnetic Field outnumbers the horizontal components considerably in both Europe and North America, vertical fluxgate gradiometers have no disadvantages compared total field magnetometers in the field of UXO detection.

Of more significance is an observation that was recently reported in the literature [Ripka 2007]. It has been observed that in some orientations of objects and magnetometers, the scalar field gradient measured with resonance magnetometers is very small (below 0.01 nT/m) while at the same time the vectorial gradient is easily measurable (10 nT/m).

Factors that are more important than the choice of the magnetometer as discussed above include the following:

- High density of data points: with signatures of many larger UXO items covering only 50 m² to 100 m² in a noisy background, it is paramount to maximize the number of data points in the particular area. The more data points are available, the more likely it becomes to detect objects with weak magnetic anomaly amplitudes. Therefore, even when surveying of unexploded bombs, the sensor separation should be 0.5 m and the data point separation along the tracks of each individual sensor 0.05 m or 0.1 m at maximum.

- Georeferencing: In UXO surveys, it is important to locate all measurement points correctly using RTK-DGPS georeferencing and inclinometer / gyrometer corrections in underwater surveys. Measurement points that are not located with high precision will appear as noise rather than representing the anomalies from which they originate. Therefore, even for underwater surveys, georeferencing should be better than ± 0.5 m.

- Multi-channel surveys: The more sensors are moved over an area on a fixed array, the better the quality of the data will be because the sensors will not change their position individually. Thus, the chance of surveying a large part or even a complete anomaly in one consistent swath will improve.

- Equidistance between magnetometers and surface: It is paramount to keep the distance between magnetometers of an array and the surface at a constant value for the whole survey. Variations in the distance between the magnetometers and the surface will result in distorted signatures of the UXO objects searched for and increased noise levels as the amplitudes of geologic origin will vary with the varying distance.

Conclusions

Considering the brief discussion of the advantages of scalar resonance and vectorial fluxgate magnetometers above, it becomes clear that fluxgate vertical gradiometers are equivalent to scalar magnetometers despite their nominally smaller resolution because the effective resolution is determined by noise during a survey.

It has also been discussed that in some cases the measurable anomalous signature is higher for a fluxgate magnetometer than for scalar magnetometers and that object calculation with respect to position (X, Y, Z) and size is more precise and reliable with fluxgate vertical gradiometers because the directional information is contained in the dataset.

Other factors apart from the choice of the magnetometer have more impact on the result in terms of resolution for the dataset and the detectability of UXO signatures.

Therefore, if the fluxgate vertical gradiometers are used on a fixed array, the distance between the sensors and the surface being investigated is kept adjusted during a survey and georeferencing is good, a survey with a fluxgate vertical gradiometer will not be inferior in any way to a survey with scalar resonance magnetometers.

Only in equatorial latitudes, where the horizontal component of the Earth magnetic field dominates, scalar magnetometers are advantageous over fluxgate vertical gradiometers.

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