Canadian Archaeological Association
Association canadienne d'archéologie

Magnetometer

Recommended Data Collection Procedures for Locating Unmarked Graves

Introduction

While Ground Penetrating Radar (GPR) is one of the most common and reliable remote sensing techniques for locating unmarked graves, communities should be aware that there are numerous other approaches available. This is important, as there are circumstances where GPR survey does not work, such as areas with unsuitable soil types that prevent radar penetration, or areas with heavy vegetation that prevents the radar antenna contacting the ground. In instances such as these, we need to look for alternative approaches. Furthermore, even where GPR does work, it is considered best practice to apply multiple techniques to remote sensing projects, as each provides its own distinct data set that can offer different insights on features of interest and help confirm the presence of a grave, thereby improving confidence in the results. The following provides a brief overview of *magnetometer survey*, one of the most commonly used remote sensing techniques in archaeology. It is intended as a brief overview to provide communities with enough information to work with remote sensing specialists to achieve the results they want and need.

Magnetometer survey is one of several magnetic geophysical techniques that measure differences in the Earth's magnetic field and/or differences in the magnetic properties of the ground. These differences can occur for numerous reasons, including instances where the ground is disturbed, as is the case when a grave is dug and refilled. This is because topsoil (the layer of earth closest to the surface) usually has slightly higher magnetic properties than the underlying subsoil, as it contains more and different forms of iron minerals. When a grave is dug and refilled, the topsoil and subsoil are often mixed together, and as a result the soil in the grave shaft has different magnetic properties than the surrounding area. These differences are tiny and we need specialized instruments to detect them (Figure 1). Metal detectors are not appropriate for this type of survey as they are not sensitive enough and usually only penetrate to a maximum depth of 30cm.

Figure 1. Magnetometer survey for 3 unmarked European graves in Mercy Bay, NWT. Instrument: Geoscan FM256 fluxgate gradiometer.

Identifying graves through magnetometer survey, like any remote sensing approach, is challenging. The potential success of a magnetometer survey will depend on a number of factors. The most important is the degree to which the fill of the grave differs from the surrounding subsoil. Usually, the difference is very small, so sometimes identifying the grave is impossible and other approaches are needed. Pieces of iron in the grave, such as coffin nails or hardware, might be detectable in relatively shallow graves, but it is usually impossible to distinguish these from other pieces of buried metal that commonly litter the ground. Magnetometer survey will therefore, in most instances, be used as a supplemental survey technique to ground-penetrating radar (GPR) to improve confidence in the results.

Magnetometer survey will also play an important role in situating the results of GPR, particularly in instances where large areas need surveying. This is because magnetometer survey is one of the fastest geophysics approaches available, which allows for large areas to be surveyed quickly. Magnetometer surveys can identify buildings and other features that are remembered by survivors or identified in archival records but may no longer exist above ground. Locating where these buildings and features are in the landscape will be invaluable in helping to guide GPR investigations to areas of greatest potential.

Like most geophysical techniques, magnetometer survey does not disturb the ground. Indeed, most magnetometers are carried above the ground and are passive, meaning that they simply measure tiny changes in the Earth’s magnetic field rather than emiting energy into the ground to measure a response.

1) Planning

Not all soils or locations are suitable for magnetometer survey (e.g. igneous geology or urban environments). Furthermore, areas of 19th or 20th century habitation, such as residential schools, are often strewn with ferrous waste (nails and other small pieces of iron from old buildings and refuse dumps) that seriously impede magnetic survey. The area that you wish to survey should be investigated prior to conducting a magnetometer survey to assess the likelihood of success and to establish the best survey methodology. This can be achieved by examining historical borehole logs and water well records, or conducting a small pilot project that surveys a small area of the site to determine if the local conditions are likely to yield positive results. This can save both time and money and avoid disappointment. Additional time and expense can be saved if potential burial areas are identified through survivor testimony and archival research prior to the survey. Many magnetometers must be held extremely still and require uninterrupted data collection along survey lines that must remain straight. Even small obstacles, such as small bushes, can seriously impede the survey and add considerable time and expense. It may be necessary to prepare the survey area to remove low vegetation and long grass. Areas close to fence lines, parking lots, buildings and other sources of metal are not suitable for magnetometer survey.

Mapping the survey area and the management of the resulting spatial data is a critical aspect of any remote sensing project. The survey area(s), areas of high potential, obstacles and other landscape features should all be identified on the ground, mapped and added to a data management system (see the GIS document in this series). There are many mapping tools available, depending on the location of the work. These include high-precision GNSS/GPS, total station theodolites, handheld low-precision GPS, or even chain and compass from known landmarks. Surveyors should use the greatest precision available. GNSS/GPS and total station theodolites are the most accurate and have the advantage that most are used with computer mapping software, allowing the automatic recording and description of survey points. Chain and compass and/or hand tapes are slower, require thorough note taking, and may have repeatability issues if completed by inexperienced personnel. They may, however, be the only option as tree canopy can block GPS signals and dense undergrowth can inhibit total station survey. Regardless of the approach, the survey should be accurate enough to allow communities to relocate the position of any identified graves or other features of interest after the survey is complete. You may wish to consider marking the corners of the survey grids with plastic (not metal) tent pegs to aid in relocating grids and features identified within them, in the future.

While magnetometer survey is one of the faster ground-based remote sensing techniques, it is still time consuming. The number of individuals needed to complete a survey will depend on the instrumentation used and the site conditions, including ground cover and other obstacles. Some instruments take readings more rapidly, while others might have multiple sensors, which can double or quadruple the speed of the survey. Fluxgate gradiometry is often a preferred method in archaeology, as it allows for rapid, high density data acquisition and many of the commercially available instruments allow for a set up with multiple sensors. Generally speaking, magnetometer surveys are most efficient when done by three people, though some instruments allow for fewer individuals. We estimate that a crew of three technicians can conduct a mapping survey of about 3000 – 6000m^2 in one day, depending on conditions and instrument used. Such surveys require permissions, access, and the development of agreements on scheduling, deliverables, timelines, training and, if required, budgets. Communities often require specific protocols to be followed including necessary ceremonies, timeframes, and rules about comportment and behaviour when working with ancestors.

There are a variety of magnetometers available on the market, most of which are aimed at the environmental or engineering sectors, rather than archaeology. It is important, therefore, to choose an instrument that is suitable for grave detection. The most important factors to consider are sensitivity and speed of the instrument. Instruments that are capable of rapid, high density data acquisition to a minimum of 0.1nT are essential for grave detection. The most common magnetometers used in archaeology are fluxgate gradiometers and alkali-vapour magnetometers (more common in Europe). Other instruments are also suitable but may be slower or more difficult to handle. Much will depend on what is locally available, but should provide the target specifications outlined above.

2) Data Collection Protocols

The recommended methodology for data acquisition will differ depending on the goals of the survey. Archaeologists often differentiate between two types of survey methodology: *reconnaissance survey* and *mapping survey*. Reconnaissance survey is where a large area is surveyed at lower resolution to identify the general location of a large target of interest (e.g. a cemetery). Mapping surveys are used to cover smaller areas at higher resolution to map the distribution and number of individual features (e.g. graves) within them. Reconnaissance surveys often precede a mapping survey and have the potential to save both time and money by helping to pinpoint areas of interest quickly and efficiently over a large area. Any area of interest identified in the reconnaissance survey can be further investigated through a higher resolution mapping survey to provide greater detail. However, reconnaissance surveys, due to their lower resolution, can miss small, ephemeral features such as graves that are difficult to locate. Given the higher speed of magnetometer survey compared to other remote sensing techniques, communities may wish to forgo reconnaissance survey and consider investigating the entire area with a higher resolution mapping survey, once they have established that the approach is applicable.

While many magnetometer instruments can be configured to allow data collection with an integrated GPS, most are not accurate enough to provide the resolution necessary to identify graves. It is also harder to keep track of where you have surveyed with a GPS system, leading to inconsistent data densities, and in some cases, for areas to be missed entirely. The CAA therefore recommends that all magnetometer surveys are conducted within grids. Common grid sizes for magnetometer surveys are 10 m, 20 m and 30 m squared. It is sometimes helpful to conduct surveys within rectangular shaped grids to avoid inadvertently confusing the orientation during processing. However, some instruments do not allow for this, and errors can be avoided by accurate note taking. Unless the survey area is small, grids should be established using a total station or GNSS/GPS to an accuracy of 5 cm. For small areas (e.g. 20 m x 40 m) laying the grid out with tapes should suffice.

Unlike GPR, targets of interest are best surveyed at approximately 30 degrees to their orientation (if known), as some processing functions can remove responses from buried features (particularly those that are linear) when crossed in line with their orientation. However, in practice, the alignment of features is often unknown prior to the survey. Grids are more often set up in relation to obstacles or field orientations on the ground. More importantly, as magnetometer survey is likely to be used alongside a GPR survey, it would be more expedient to use the same grid as the GPR survey, which should be set up perpendicular (90 degrees) to the orientation of the grave(s) (if known). The corners of the grids should be recorded with GNSS/GPS so that their location can be re-established, and any features of interest identified within them located.

Magnetometer survey is performed by carrying, pushing or pulling a magnetometer back and forth within grids that have been laid out over the ground. Tapes and ropes are used to guide the operator in this process and to ensure the entire area is covered.

The following survey criteria are recommended:

Reconnaissance Survey

- Survey grids should be laid out with a total station theodolite or GNSS/GPS
- Grid corners should be located with a GNSS/GPS to within 5 cm accuracy.
- A minimum point sample density of 0.5m x 0.25 m is recommended (e.g. readings recorded every 0.25 m along traverses spaced 0.5 m apart).
- Data collection within grids using either zig zag (bi-directional) or parallel (unidirectional) traverses is recommended over GPS enabled data acquisition.

Mapping Survey

- Grids should be laid out with a total station theodolite or GNSS/GPS
- Data collection within grids using parallel traverses is recommended to reduce collection errors such as traverse striping and staggering.
- Minimum traverse spacing of 25cm with inline sample density of 12.5 cm or less (e.g. 6.25cm).

3) Data processing, interpretation and presentation

Once the survey is completed the survey data needs to be processed in computer software to generate plots for interpretation and presentation. The plots look very much like air photographs taken from above (Figure 2). Processing magnetometer data can require numerous steps as the Earth's magnetic field is constantly changing, resulting in numerous natural effects in the data that need filtering out. Data collection inconsistencies are also common due to the sensitivity of the instruments. It is important that the processing steps are done in the correct order as each filter will affect subsequent steps.

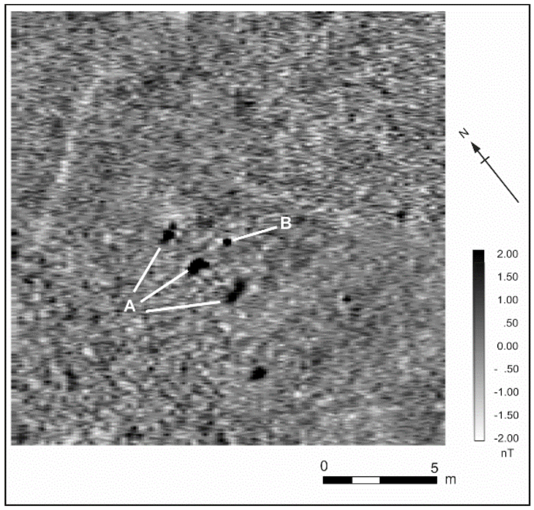

Figure 2. Example of gradiometer results showing the location of 3 unmarked graves of 19th century European sailors (A) in Mercy Bay, NWT. The results also identified what is believed to be the foundation of the original grave marker (B).

Data processing should follow the sequence of steps recommended by the instrument manufacturer and software used. These might include, but are not limited to: 1) a review of the raw data, 2) clipping data to remove noise spikes that affect statistical calculations of subsequent processing steps, 3) neutralising major responses (e.g. fence lines and services), removal of data collection defects (e.g. traverse stripping or staggered data), iron spike removal to remove responses of near-surface metal (caution is needed as iron coffin fixtures and nails may be the only indicator of the presence of a burial), final enhancement of data plots including smoothing and interpolation (Figure 3).

Magnetometer survey data can be difficult to interpret and should be done by trained individuals. For example, the shape and size of the magnetic response that results from a buried feature or object may look completely different to its actual form. A small iron object such as a nail results in a positive and negative magnetic response which is observed in the data as a black and white image, the shape of which depends on the orientation of the object (Figure 4) but none of which look anything like a nail. The size of the nail's magnetic response will also be much larger than the nail itself and might measure up to one metre on the plot. Buried services, in particular metal pipes, or fences running along property boundaries can produce enormous responses that appear many meters wide, "washing out" any of the subtle detail that might be produced by graves in those areas, and rendering the survey useless.

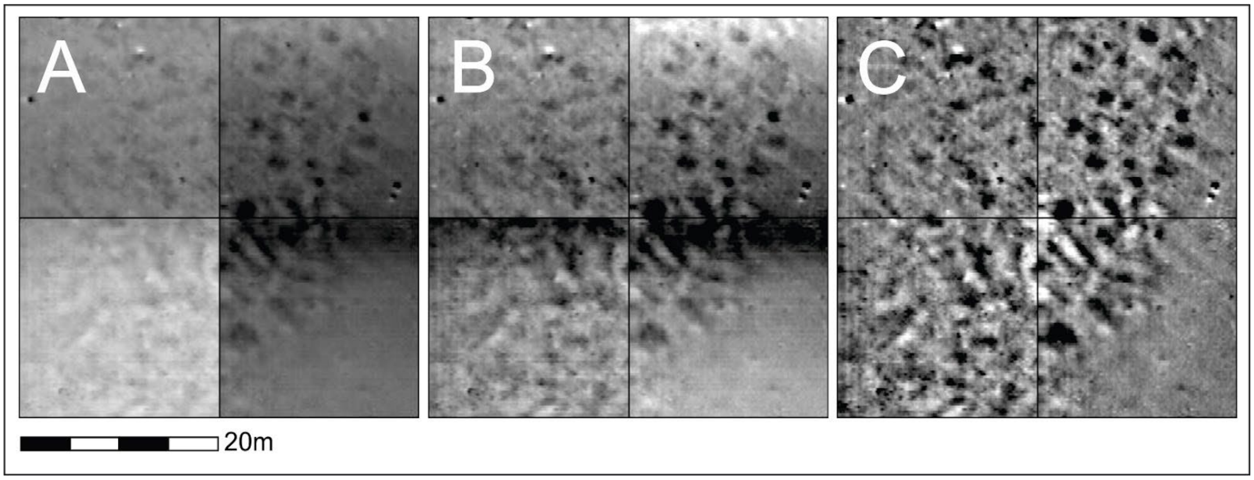

Figure 3. Example showing how some of the processing functions change and enhance the data plots to aid interpretation (Note: Processing terminology may differ between software). A: Raw results showing mismatch of responses between and across grids due diurnal variation (natural changes to the Earth's magnetic field during the day). B: Results after Zero Mean Grid function applied to help match grid data and C: Final results after “Zero Mean Traverse” and “clipping” applied to remove slope effects in data and to enhance the contrast of features of interest.

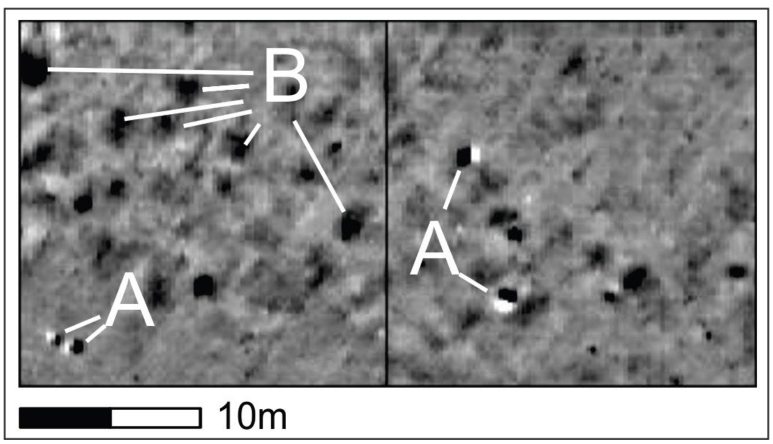

Figure 4. Example of gradiometer results with responses resulting from small iron objects buried in the soil. Note that while they are likely less than 10cm in size, they appear over 1m wide in the plot, almost as large as the archaeological pits (B) which were the focus of the survey.

Interpretation of geophysics results also inevitably includes different levels of confidence. For example, an archaeologist might assign a 70% confidence level that graves exist in a location, depending on how clear the results are. This is where having other sources of evidence, such as other remote sensing techniques or survivor testimony is beneficial, as multiple lines of evidence that all point in the same direction will provide more certainty. The survey report should make a clear distinction between different levels of confidence including inferences based on scientifically demonstrable criteria from those arising from informed speculation based on prior experience.

4) Presentation

The final report should include:

- Copies of unprocessed raw data should be included with the report for archiving.
- A brief site description indicating underlying soil types and geology, ground conditions and vegetation, description off built architecture, pervious disturbance including previous archaeological investigations and known underground services that might impact the results.
- Photographs, if appropriate, of each survey area showing the ground conditions.
- The survey methodology should provide a description of the instrumentation used and indicate the traverse line separation/direction, inline sampling interval and the resulting effective spatial resolution achieved.
- A map showing the location of survey grids in relation to other features at the site.
- All location maps must be geo-referenced and annotated with the geographic coordinate system and projection used in order that the location of the grids can be re-established by a third party.
- Plots of minimally processed data should be included prior to the presentation of more fully processed plots.
- All data processing steps should be described in full and their effects on the data highlighted.
- Anomalies resulting from data collection errors that cannot be removed through data processing should be described and distinguished from other responses.
- The interpretation should distinguish anthropogenic from other causes of magnetic enhancement.
- Separation of negative and positive magnetic features and areas of statistically different activity should be described where appropriate.
- Estimate of the depths of features should be calculated (e.g. through half-width rule.)
- Grey scale plots are generally recommended over false colour maps, due to their ability to differentiate subtle detail. False color should only be used in instances where delineation of features of interest might benefit from highlighting through

colour. All plots should include a north arrow, range bar including appropriate values and units, and be presented in and include an appropriate scale for interpretation.

- Interpreted plans indicating all features of interest should be included alongside the data plots.
- Anomalies of interest should be identified with a unique identifier on the plots, and described in full to indicate shape, polarity and signal amplitude. This might best be achieved in a table rather than a long descriptive narrative.

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