Magnetics: Fundamentals and Parameter Extraction
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Magnetic module outline

Magnetics fundamentals
- Sensor systems
- Data examples and demo

Parameter extraction
- Concepts
- Real-world examples

Classification
- Using the parameters to make discrimination decisions
Standard processing stream

- The standard processing stream for detection and classification of UXO using geophysical data

1. Data Collection
2. Parameter Estimation (Target Attributes)
3. Classification

Schematic showing the standard process flow of a digital geophysical survey. The data are collected and captured by a data logger. After the survey is finished, the data are typically transferred to another computer where initial data processing and then parameter estimation are performed. The parameters are then used to make classification decisions.
Detection of metal with a magnetometer

- Most ordnance contain ferrous metal
- Ferrous metal causes a distortion of the Earth’s magnetic field

The Earth has a magnetic field whose direction and magnitude varies across the surface of the Earth. Within most of North America, the magnetic field lies within 10 degrees of true-North and is oriented at about 65 degrees from horizontal. Magnetic “field-lines” are straight when there is no metallic object present. When a ferrous object is introduced, the field lines become distorted and are essentially attracted into the object.
The distortion of the magnetic field caused by a compact object like a UXO can be approximately modeled as a magnetic dipole (essentially a bar-magnet with a north and south pole on either end). The magnetic field lines leave one end of the object (the south-pole) and wrap around and re-enter the object at the other end (the North pole). Most magnetometers in use today measure the total magnetic field. The Earth’s field is large (around 50,000 nT) compared to the distortions caused by buried metal (typically 1 to 1,000 nT).

By subtracting off the Earth’s field, we see that the total-field “anomaly” caused by a buried object is positive when the field from the object is in the same direction as the earth’s magnetic field and negative when it is in the opposite direction. In the Northern hemisphere this causes a positive lobe to the south and a negative lobe to the north of the buried item.
Examples of magnetometer data collection systems. Each of the systems has one or more magnetic sensors, a positioning system (either Global Positioning System or Robotic Total Station) and a data logger for digital capture of the sensor and position data.
Schematic of magnetometer data collection. Data are collected along nominally straight pathways at a desired lane spacing. Each black dot shows the location of a magnetic measurement with the magnetic data shown in red. Positive values lie above the measurement plane, with negative values below.
Screen shot of the data collection animation
Screen shot of the data collection animation
Screen shot of the data collection animation, showing a gridded image of the data in plan view. The magnetic data are plotted using the color-scheme shown by the color-bar at right. For instance, any regions where the magnetic field is 70 nT are colored red, while regions with -10 nT are shown in blue.

The anomalous field is plotted here; the Earth’s field has been subtracted from the measurements.
Screen-capture of the set-up used for real-time demonstration of magnetic data.
As the depth of the item increases, the amplitude decreases and the distance between the positive and negative peaks increases. The amplitude decreases as the third-power of distance away from the sensor. The effect of increasing the depth by 10 cm while keeping the sensors the same distance from the ground is the same as increasing the sensor distance by 10 cm without changing the burial depth.
As the size of the item increases so does the magnitude of the magnetic anomaly that it creates. The amplitude increase is proportional to the diameter of the object. Thus, if the object diameter is doubled, then so is the magnitude of the anomaly.
The magnitude and shape of a magnetic anomaly depends on the orientation of the buried object. The amplitude is largest when the long axis of the object is aligned along the direction of the Earth’s magnetic field and is smallest when oriented perpendicular to that direction.
Signal to noise ratio (SNR), as the name suggests, is the ratio of the amplitude of the signal relative to the amplitude of the noise. Thus SNR can be varied by changing the characteristics of either the signal or noise. For a given munition at a given depth and orientation, the SNR decreases as the noise measured by the sensor increases. The lower the SNR the lower the detection probability and the harder it becomes to extract parameters that reflect the intrinsic attributes of the buried object. At a fixed noise level, the SNR is also decreased by increasing the depth of the object.
The distance between adjacent sensor paths (the lane spacing) needs to be small enough to capture the full character of an anomaly. In this example, information on the shape of the anomaly is lost as the lane-spacing is increased from 25 cm to 75 cm.
Error in the position of the sensor when it takes a magnetic measurement distorts the measured magnetic anomaly.
Data collection summary

- Item attributes impact the shape, size and amplitude of the anomalous magnetic field:
  - Depth;
  - Orientation;
  - Size of UXO

- Sensor attributes that effect the quality of the data
  - Sensor noise
  - Line spacing
  - Positional error
  - Sensor height above ground (and any variation)
Detection performance

- Detection performance is dependent on
  - Object size
  - Noise
  - Data density

This slide shows how the amplitude (measured as the difference between the positive and negative parts of an anomaly) of a 4.2” mortar varies as the depth below the surface is increased. There is a significant difference between the least favorable (mortar at right-angles to the Earth’s magnetic field) and most favorable (mortar parallel to the Earth’s field) orientation. Also shown are the amplitudes of magnetic anomalies observed over 100 different 4.2” mortars that were seeded at Camp Sibert, Alabama. The magnetic sensor was 30 cm above the ground. An example noise floor of 10 nT is marked on the graph.
The smaller the object, the smaller the anomaly amplitude and hence the shallower the “detection depth”. This is evident in the above plot where the 60 mm anomaly amplitude intersects the notional 10 nT noise line at shallower depths than the 4.2” mortar. At more favorable orientations, the anomaly amplitude remains above the noise floor to greater depths.
Target picking processing flow

- Magnetometer data are collected along survey lines
- Geophysicist reviews and processes the profile data
  - “Bad data” are rejected (e.g. out-of-range)
  - Filters are applied to suppress diurnal changes in the magnetic field and longer wavelength features due to geology
- Data are generally “gridded” to produce an image of the magnetic data
- Regions of anomalous response are selected as potential metallic targets

The above represents the standard processing flow used for digital geophysics.
Anomaly identification
Total-field data from Montana

- "Raw" total-field data from a 100 m by 100 m area at Chevallier Ranch Montana

This slide shows a three-dimensional perspective view of the magnetic field over a 100 m by 100 m area of the Chevallier Ranch site in Montana. Sub-surface metallic objects cause localized distortions in the measured magnetic field. More extensive, largely linear features in the magnetic data are caused by variations in the magnetite content of the underlying geology (trending roughly east-west), or by magnetite transported along drainage channels (the north-south features).
An appropriately tuned high-pass filter (which passes the shorter spatial scale [higher spatial frequency] target response while removing the longer spatial scale [lower spatial frequency] background interference) can be used to suppress the effect of the longer-wavelength geological features while accentuating the localized anomalies caused by buried metal.
This is a plan-view of the same image as the last slide.
The locations of potential ordnance items are either selected manually or by automatic target selection methods.
The four anomalies shown in this slide were obtained by the MTADS magnetometer array at Camp Sibert, AL. Each anomaly has dense data coverage (the black dots) and no obvious distortions caused by positional or other errors in the data. Notice the apparent striping caused by background geology in the image on the lower right.
The anomalies shown in this slide were collected by a man-portable magnetometer array at Chevallier Ranch, MT, under more challenging conditions than those at Camp Sibert. The top two anomalies suffer from data gaps caused by variations in the lane-spacing as the operator avoids small bushes at the site (the black dots mark the sensor locations). The bottom two anomalies are distorted either by geology or by positional inconsistencies between adjacent traverses over the anomaly.
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Parameter extraction

- The data that are measured are an indirect indicator of what is buried under the ground.
- Inversion or "parameter extraction" is used to estimate the parameters of an underlying model that encapsulates some useful attributes of the buried object.

\[
\begin{align*}
\text{Model Parameters: } & \quad m \\
\text{Sensor data: } & \quad d \\
\text{Forward Operator: } & \quad d = g[m] \\
\text{Inverse Operator: } & \quad m = g^{-1}[d]
\end{align*}
\]

The data themselves do not directly tell us if the underlying object is a munition or something non-hazardous like shrapnel, range scrap or cultural debris. The objective of parameter extraction is to estimate the parameters of an underlying model that encapsulates some useful attributes of the buried object. The forward problem involves estimating the magnetic anomaly caused by an object with particular attributes. The parameter extraction, or inverse, operation is more difficult and involves estimating the object attributes from the measured data.
Screen-shots of a real-time demonstration of parameter extraction. The “observed data” are shown on the left. The data that would be produced by an initial guess at the underlying target attributes are shown in the center. They do not provide a good match to the data. The parameter extraction method (in this case we use physical intuition) adjusts the azimuth so that the orientation of the modeled anomaly now looks correct (the size and shape of the anomaly are still wrong at this stage).
The modeled data in the middle panel produce a smaller anomaly than what was observed. The modeled data agree much better with the observed data after the target is pushed deeper. The anomaly amplitude still doesn’t agree.
The depth and orientation are correct but the size is wrong. The amplitudes of the observed and modeled data match closely after increasing the size of the target.
The parameters that provide the best-match to the observed data reflect our best estimate of the target attributes of the underlying object.
Parameter extraction

- The demonstration we have just seen described one method of parameter extraction
  - Search by trial and error with a visual assessment of what model fits the best
- In practice, highly efficient automated parameter extraction techniques based on non-linear least squares are used
  - The objective is to minimize the difference between the actual and predicted data
A magnetic dipole is used as the underlying model for parameter extraction from magnetic data. The dipole is equivalent to a bar-magnet, whose lateral position, depth, orientation and magnitude need to be estimated.
Example of a dipole model fit to magnetic data collected at Chevallier Ranch, MT. The panel shows the observed data (top left), modeled data (top-right), residuals (which are the difference between observed and modeled data, bottom-left) and extracted parameters (bottom right). While the estimated lateral position and depth are important, they don’t tell us anything substantial about the possible identity of the object. The moment, azimuth and dip, which encapsulate the size and orientation of the underlying dipole, provide information on the likelihood that the underlying object is a munition.

The parameter extraction technique returns an estimate of the “fit quality” which is an indicator of the reliability of the parameter estimates. If the fit-quality is low, then there is considerable uncertainty in the values of the underlying target attributes. In this case the fit-quality is high.
Another parameter extraction example from Chevallier Ranch. In this case, the moment is about $1/10^{th}$ the size of the previous example.
Magnetics

Can’t analyze

Could be 2 anomalies or a mismatch in position on adjacent passes

Easting (m)

Northing = -0.31 m

Depth = 0.26 m

Moment = 0.05 Am²

Azimuth = 95.5°

Dip = -13°

Fit quality = 0.82

For some anomalies the data are not of sufficient quality to support reliable parameter extraction. We refer to these as “can’t analyze” anomalies

Example of an anomaly with low fit quality. In this case, we can’t rely on the extracted parameters and would place the anomaly in a “can’t analyze” category. In the absence of further information, this anomaly would need to be treated as a potential target-of-interest.
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Classification

● The objective of a UXO remediation strategy is to produce a prioritized dig-list with an indication of how many items have to be excavated as potential UXO.

● The topic will be covered in detail by Dean Keiswetter in a later module.

● Here we just provide an example of ranking the dig-sheet based on the size of the moment.
The example that follows comes from Camp Sibert, AL where the objective was to recover all 4.2” mortars while leaving as much clutter in the ground as possible.
**Size versus amplitude**

- Ranking by amplitude results in significant overlap between all classes
- Overlap is reduced considerably when ranking by size of object

The bar-chart at left provides histograms of the amplitude response (difference between positive and negative lobes of the measure anomaly) from

1. Shrapnel and cultural debris (or junk)
2. Base-plates
3. Partial rounds; and
4. Intact 4.2 inch mortars

Most of the shrapnel and debris have low anomaly amplitudes. The 4.2” mortars tend to have higher amplitudes, but there is a considerable range in values. To recover all 4.2” mortars would require digging up almost all of the clutter items.

The bar-chart at right shows histograms of dipole moments obtained through parameter extraction. The smaller items (shrapnel, base-plates) tend to have small moments and can largely be distinguished from the larger 4.2” mortars which have larger estimated moments. Many clutter items could be left if the dig-sheet were prioritized based on the size of the moment.
**Summary 1**

- Ferrous ordnance and non-ordnance distort the Earth’s magnetic field
- Cesium-vapor total field magnetometers are used extensively in ordnance detection applications
- Magnetic anomalies depend on the size, shape, orientation and depth of the buried object
- Survey parameters such as sensor height, sensor noise levels, position errors and lane-spacing effect the quality of the collected magnetic data

**Summary 2**

- Parameter extraction routines are used to estimate the attributes (size, orientation, depth) of a detected buried object
- The extracted parameters are used to create a prioritized dig-list
- Magnetic data are largely immune to sensor orientation, can be rapidly collected and are highly sensitive to the depth of the buried item
- Magnetic data can be adversely affected by geology, only return an approximate estimate of the object’s size and can’t be used to (uniquely) determine the object’s shape.