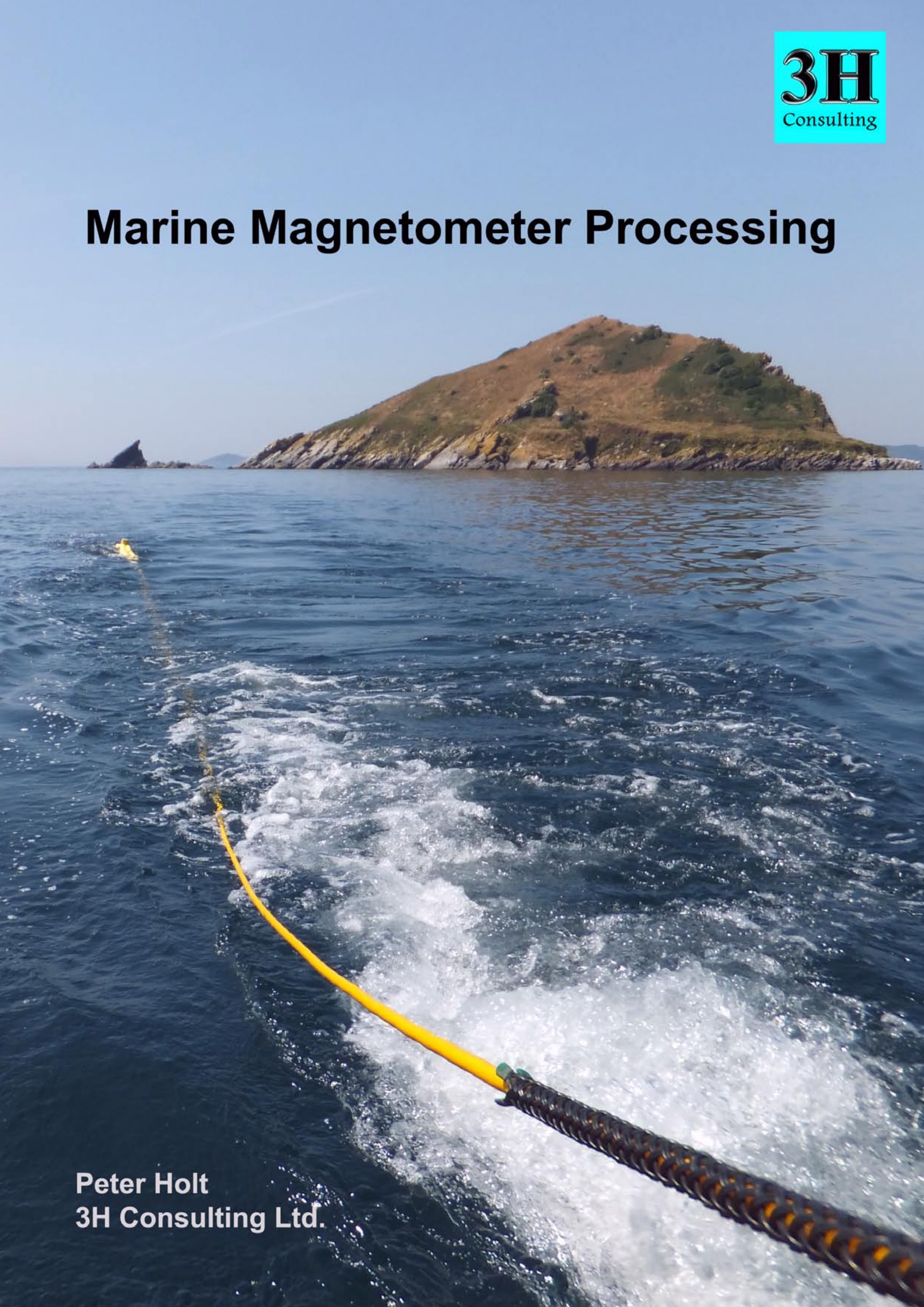
3H
Consulting

Marine Magnetometer Processing



Peter Holt
3H Consulting Ltd.

Marine Magnetometer Processing

Peter Holt
BEng CEng CMarEng MIMarEST MCIfA MHydSoc

Director, 3H Consulting Ltd.

Visiting Research Fellow (2011-2016)
School of Geography, Earth and Environmental Sciences, Plymouth University

First published May 2014, 2nd edition 2019

Published by 3H Consulting Ltd., Plymouth

pete@3HConsulting.com
www.3HConsulting.com

Front cover: Geometrics G882 caesium magnetometer towed on the surface in very shallow water, SHIPS Project 2013
Back cover: Marine Magnetics SeaSPY Overhauser magnetometer being deployed from Plymouth University’s survey boat *Falcon Spirit* during MSc Hydrography fieldwork in 2012.

Acknowledgements

This book is the result of a number of years research and field trials that have involved many people, but most significantly Kevin Camidge at CISMAS; Gwyn Jones, Martin Davis, Dave Crampton, Arthur Laloe at Plymouth University; Armin Schmidt at the University of Bradford, Doug Hrvoic at Marine Magnetics Ltd., and Nigel Boston at Geosa Ltd.

Contents

1. Introduction to Magnetometer Processing

This guide is about processing data from marine magnetic surveys undertaken to locate and map archaeological sites underwater.

The aim of this guide is to show how to take a set of information recorded from a marine magnetometer survey, to explain what it means and to enable you to produce some useful results. The most usual requirement is to be able to identify any significant objects on the seabed, known as *targets*, within an area of seabed surveyed using a magnetometer. The targets can then be investigated using other remote sensing methods or directly by divers or an ROV. In this guide, data processing is explained from the basic principles to more advanced methods, followed by sections on producing reports and charts from the processed results.

Marine magnetic surveys that are undertaken to investigate shipwrecks and other archaeological sites usually cover a small area, but are done in great detail so the smallest iron (or steel) objects can be detected. Marine magnetic surveys for archaeology push the capabilities of the equipment and processing to the limit as the aim is to detect the smallest iron objects, despite often unfriendly environmental conditions and limited budgets.

Iron and Steel
A magnetometer will detect ferrous or iron-based metal; this includes wrought iron, cast iron and steel. In the book we will just refer to iron but this includes all ferrous or iron-based metals.

Magnetometer surveys are also undertaken for other reasons, although the basic principles are the same the processing is done differently:

- Processing data from archaeology surveys on land requires different techniques. The data from this kind of survey is usually much more detailed and distance from the target to the magnetic sensor is small, so much smaller anomalies can be identified. Coverage of the site is usually greater so it is easier to produce meaningful contour and 3D surface plots.
- The processing method used for large scale geological surveys is different as the size of the geological features is usually much larger than the survey line spacing.
- One field where the data processing is similar is unexploded ordnance (UXO) detection as the targets are of a similar size and the environment is the same.

This guide provides only a little information about data collection for marine magnetic surveys and only that which affects data processing. It includes a very basic explanation about the different types of marine magnetometer currently available but only including details which affect the quality and quantity of measurements that each type collects. The rate at which measurements are made, the amount of noise in the data, the position of the towfish relative to the target and many other factors also are discussed.

There words used in the guide are intended to be as non-technical as possible but the technical terms that have to be included are described in the Definitions section.

This guide will be revised periodically so please send an email with any questions or comments as that will suggest improvements to be included in the next version.

2. Definition of Technical Terms

Altimeter	An instrument for measuring the height of a towfish above the seabed
Anomaly	A variation in the magnetic field measured by a magnetometer
Background field	The magnetic field value in an area that is not affected by iron objects
CSV	Comma Separated Variable, a common computer file format
Distortion	A bend or a change in shape
Diurnal variation	The change in magnetic field over time caused by the effects of the sun
Ferrous	Ferrous metals are based on iron and many have magnetic properties
Field strength	A measure of the magnetic field at a point
gamma	The Imperial units of magnetic field strength, equivalent to a nanoTesla (nT)
GIS	Geographic Information System, a computer program designed to show maps, survey results and other spatial data
Gradiometer	A multi-sensor magnetometer that measures difference in field strength between two or more points
Induced magnetisation	The magnetic field of an object caused or induced by the Earth's magnetic field
Magnetometer	An instrument for measuring magnetic field strength
Metal detector	Pulse Induction metal detectors can detect many types of metal, they generate their own magnetic field and are not magnetometers
Minimum Detectable Target (MDT)	The target with the smallest mass of iron that can be reliably detected
nanoTesla (nT)	The SI units of magnetic field strength, equivalent to a gamma
Noise	The unwanted part of any magnetometer measurement. Each measurement is a combination of Signal and Noise
Noise floor	The noise level measured by a magnetometer without any magnetic anomalies present. The lower the noise floor the smaller the anomalies that can be detected.
Regional field	The magnetic field value in an area that is not affected by iron objects
Remanent or permanent magnetisation	The magnetic field that an object would create if the Earth's magnetic field was not there
Residual field	The magnetic field values in an area once the Regional field has been removed
Sample interval	The interval in metres between each successive measurement
Sample rate	The rate at which the magnetometer makes measurements
Signal	The value magnetic field strength recorded by the magnetometer, with any Noise removed.
Target	A feature or object causing an Anomaly, usually made of iron or steel
Time-Series Plot or TS Plot	A graph showing how magnetic Field Strength changes over time
Wave noise	Noise in the magnetometer measurements caused by waves in the sea moving the magnetometer up and down.

3. Basic Operation

A magnetometer is an instrument that measures the Earth's magnetic field. A magnetometer can be used to locate submerged or buried iron objects both on land and on the seabed. Iron and other magnetic objects bend the Earth's magnetic field around themselves, changing the shape of the magnetic field. A magnetometer can be used to measure the changes in the magnetic field around an iron object and these measurements can be used to detect the presence of the object itself.

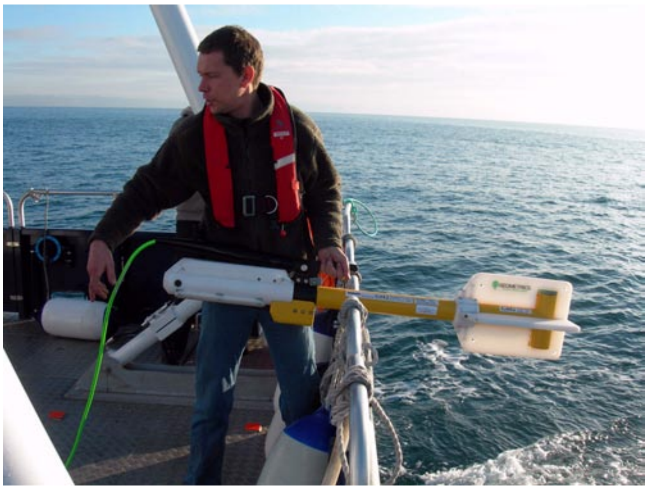


Figure 1: Geometrics G882 caesium magnetometer

Magnetometers used for marine surveys are passive, they do not transmit any signals, so do not have a working 'range' like a marine sonar. How far away they can detect an iron object largely depends on the size and shape of the object itself and how it lies within the Earth's magnetic field; the object will bend the Earth's magnetic field and the magnetometer can measure that distortion, so the bigger the effect of the object the further away it can be detected. Magnetometers are also not directional so will detect distortions in the magnetic field caused by objects anywhere around the magnetometer sensor. A magnetometer towed over a steel shipwreck will give a similar response as it would if a steel ship on the surface sailed past the magnetometer.

Magnetometers can measure changes in the Earth's magnetic field and do not directly detect iron objects. Only objects that have magnetic properties can affect the Earth's field such as iron and steel (known as ferrous materials), whereas copper, brass, wood, gold and aluminium do not. Some ceramics have magnetic properties but the effects are small and hard to detect during marine surveys. The magnetometer would have to pass very close to the ceramics to be able to detect their effect on the Earth's magnetic field, closer than can usually be achieved with towed marine magnetic surveys, making cargoes of ceramics almost impossible to detect during surveys at sea.

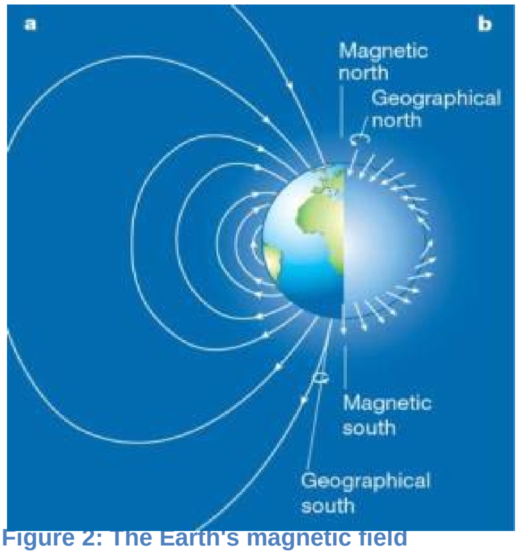


Figure 2: The Earth's magnetic field

Magnetometers are not the same as metal detectors. Pulse induction metal detectors work in a different way as they make their own magnetic field which is then affected by other types of metal. Metal detectors can detect iron, copper, brass, gold and aluminium but not wood or most types of pottery. Metal detectors have a very short range, less than 300mm (1 ft) for a typical hand held unit, so are of limited use for most marine remote sensing surveys.

The Earth has a magnetic field similar to a large bar magnet (Fig. 2). The magnetic field of the Earth is not even and uniform, it varies according to where you are on the planet. Magnetic field strength is measured in Teslas (T) but the values of the Earth's field are so small we usually refer to values in nanoTeslas (nT). Field strength is sometimes measured in gammas which are equivalent to nanoTeslas, so one gamma = one nanoTesla. The strength of the magnetic field at different places on the Earth varies from 60,000nT in parts of northern Canada to 24,000nT in Brazil (Fig. 3).

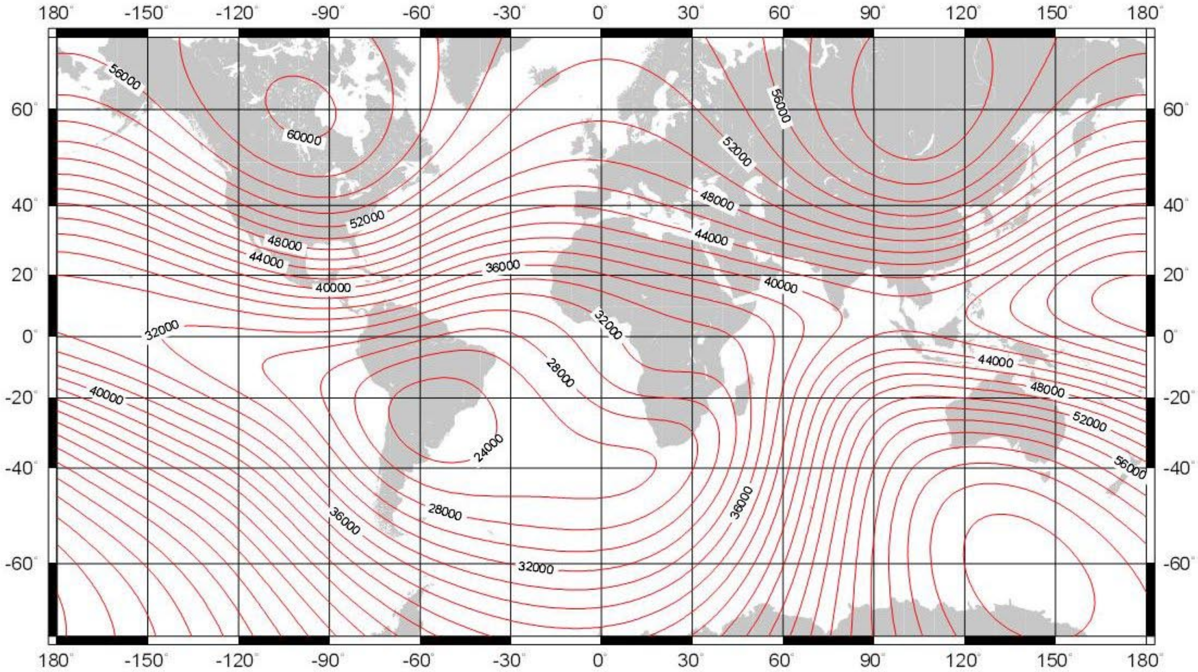


Figure 3: Geomagnetic reference field model for total field strength (BGS)

Over small areas covered by marine surveys the magnetic field does not change very much, so with no magnetic objects nearby a magnetometer would read the same value over the whole survey area.

However, many rocks are magnetic so the underlying geology can affect the magnetic field measured in a survey area. Often this is seen as a gradual change in the field measurements over the site with one area showing a higher magnetic field measurement than another. The effect is often very noticeable so magnetometers have been used for prospecting for minerals buried beneath the ground.

The magnetic field at a point on the Earth also changes with time, an effect known as diurnal variation. This is caused by the rotation of the Earth within the magnetosphere as different parts of the Earth face the sun and forms a regular daily cycle. Diurnal variation can cause the magnetic field measured at a place on Earth to be different in the morning and in the afternoon. Solar storms can also affect the Earth’s magnetic field causing large changes in the background magnetic field strength.

Figure 4: Aquascan AX2000 proton magnetometer deployed from a small inflatable boat

4. Anomalies and Targets

On a typical marine magnetometer survey the magnetometer sensor is towed underwater on a cable behind a boat. The magnetometer is connected to a computer that continuously records the magnetic field strength reported by the magnetometer as well as the position of the boat from a GPS receiver. The computer will display the measurements from the magnetometer on a time-series (TS) plot or strip chart with the magnetic field values shown on the Y axis and the time of each measurement or fix number on the X axis (Fig. 5).

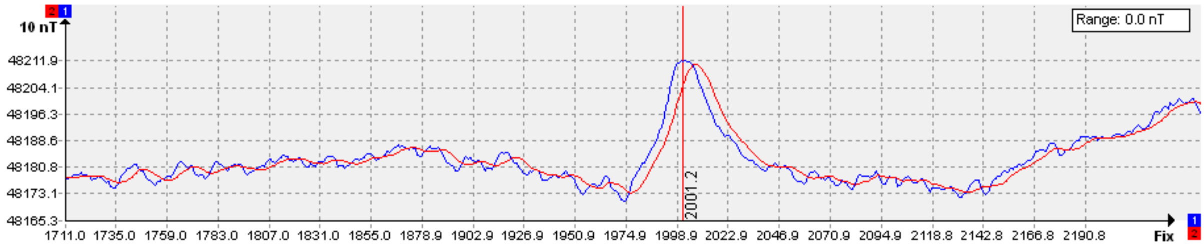


Figure 5: Time-series plot showing magnetic field strength changing over time

The blue line on the TS Plot in Figure 5 shows the raw magnetic measurements and the red line shows the same measurements slightly filtered to remove some of the high frequency noise caused by the instrument itself.

In an area where no magnetic objects can be found the magnetometer will report the same value each time and the line on the TS plot will be flat, this is known as the background field. The absolute value of the magnetic field depends on where you are on the Earth but this value does not affect how we interpret the data as we are simply looking for changes in the background field.

An iron or steel object will bend the Earth's magnetic field. Where the magnetometer comes close to that object the magnetometer will travel through the distorted magnetic field and this shows up as changes in the measurements made by the magnetometer. The TS plot on the computer will show those changes as an up and down 'wiggle' in the line, as variations above and below the background field value (Fig. 6).

The size and shape of the 'wiggle' on the line can tell us something about the object or 'target' that caused it. Interpretation of magnetometer data is complicated because the size and shape of the wiggle or anomaly measured by the magnetometer depends on where the magnetometer passes through the distorted magnetic field caused by the target. To make matters more complicated the shape of the anomaly will vary for the same object put in different places on the Earth and may also change depending on the orientation of the object. These problems are discussed further in the section on Advanced Processing.

Targets and Anomalies

A *Target* is the name given to the object that caused the *Anomaly* or bend in the magnetic field that we measured. On any survey the same Target may be detected more than once on different survey lines, each survey line would have its own anomaly but all of them would relate to just one Target.

A basic rule to follow is that targets further away from a magnetometer produce anomalies that are lower and wider, and as you get closer to the target the anomaly gets narrower and taller.

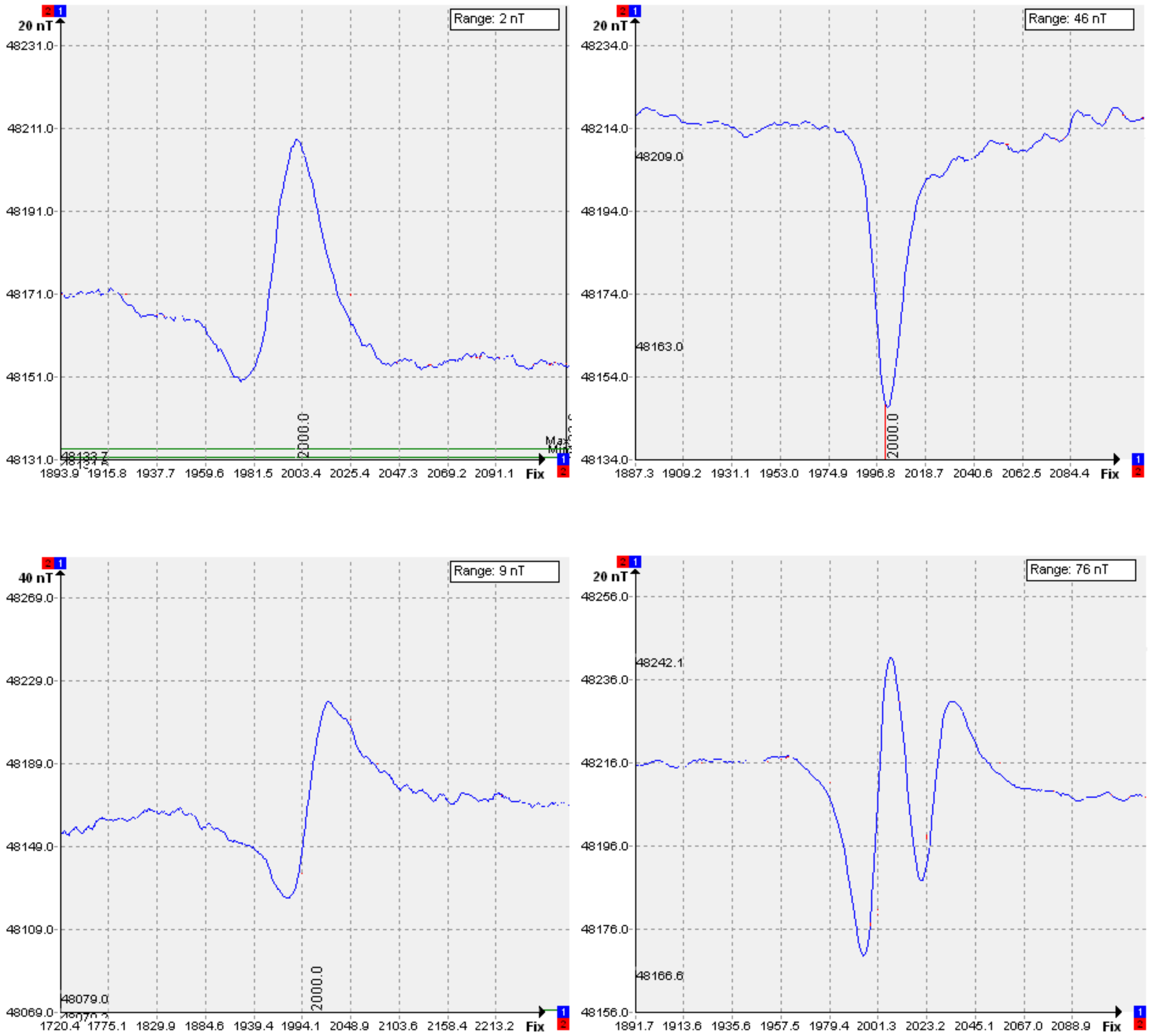


Figure 6: Time-series plots showing a number of anomalies caused by different objects

We can see the effect of a magnetic object on the Earth's magnetic field in figure 7. With no magnetic objects in the area the magnetic field would be the same value everywhere and the magnetometer reports the same value for magnetic field strength. The red flux lines in figure 7 represent the magnetic field and the strength of that field at a point is shown by the distance between each line; the closer the lines are together the stronger the magnetic field is reported by the magnetometer passing through it. Placing a magnetic object within the area distorts or bends the field making some lines move further apart while others go closer together. As the magnetometer is towed over the site it passes through areas where the flux lines are different distances apart and hence it records

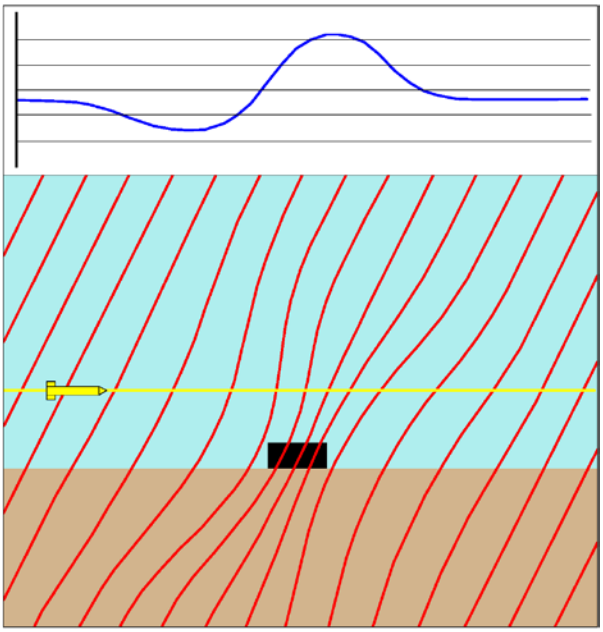


Figure 7: Distortion of the Earth's magnetic field along the yellow line, shown as a TS plot (above) and red magnetic flux lines (below)

different values for the magnetic field strength, this is shown on the blue line in the TS Plot at the top of figure 7.

The picture above shows the distorted magnetic field in two dimensions only and from the side, so it is in effect a section through a three-dimensional distorted magnetic field. From above we can show the variation in the magnetic field strength of this three-dimensional field as a contour plot where each contour is a line showing where the magnetic field is the same value. Using this picture we can show why the anomaly or 'wiggle' produced by the same target varies according to where the magnetometer is run past the target itself.

Figure 8 shows the distorted magnetic field around the wreck of the armed trawler *Elk* in Plymouth Sound. As is typical with shipwrecks in the northern hemisphere, the magnetic field shows a negative peak to the north of the wreck and a positive peak to the south. Four magnetometer survey runs across this same magnetic field would show four different responses. Run A is from west to east across the positive peak, run B is from west to east across the negative peak, C is from north to south across both peaks. Run D is from west to east between the positive and negative peaks.

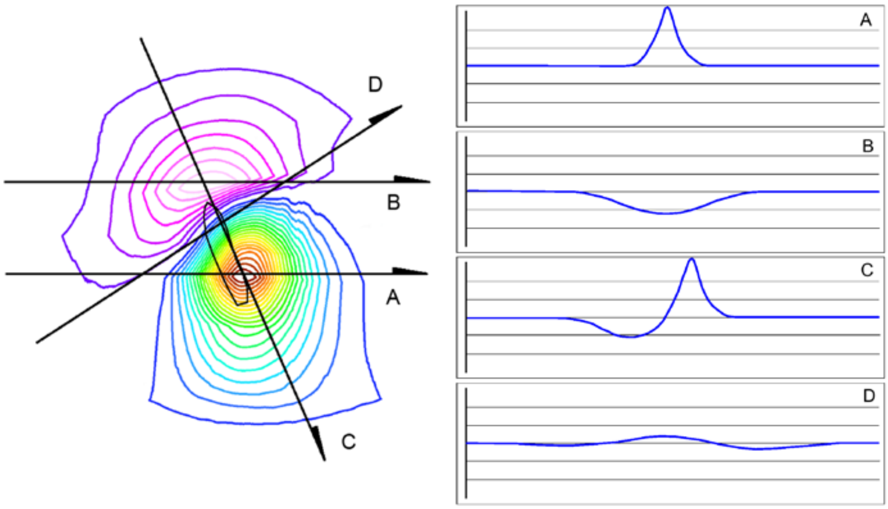


Figure 8: Magnetic field model and sections across the wreck of the *Elk* armed trawler

With this illustration we can see why the anomaly shape gets narrower and taller when the magnetometer passes closer to the target. Also, you can see in run D that is its possible to run the magnetometer right over a target and actually measure very little variation in the magnetic field. In practice the magnetic fields of many targets are not as uniform and regular as the example and some change in the field can usually be detected.

For large iron shipwrecks it is possible to make a number of runs over the wreck as the spacing between the lines is smaller than the wreck itself, so we can detect the effect of the iron on the Earth's magnetic field on more than one of the survey lines. The effect of the iron will be strongest when the magnetometer is closer to the wreck and it decreases as we move away until the distorting effect can no longer be detected. If we make a number of parallel runs over the wreck we can use it to model the shape of the magnetic field.

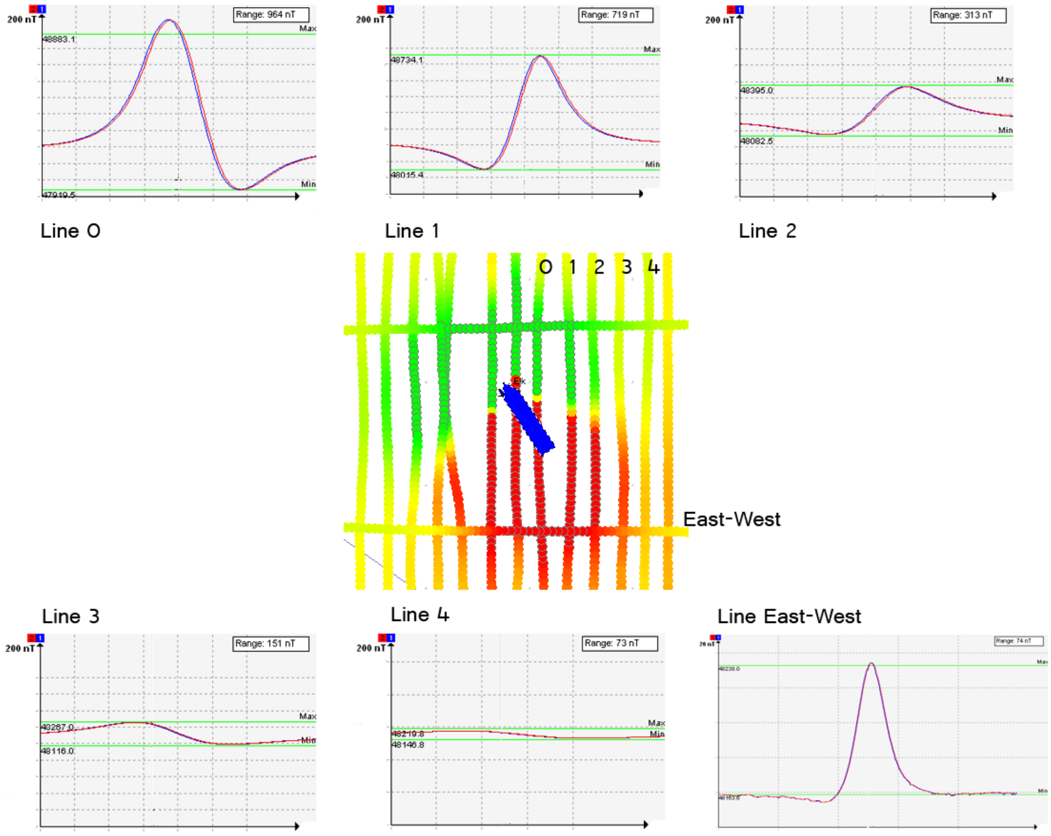


Figure 9: Magnetic field decreasing with distance around the armed trawler *Elk* off Plymouth

Results of this kind of survey can be seen in figure 9 where the magnetic field over the 30m long steel armed trawler *Elk* (outline shown in blue) was measured in a number of parallel survey lines. The strongest distortion of the magnetic field, and hence the largest anomaly, was measured as the magnetometer travelled directly over the ship's steel hull. Parallel survey lines run further away from the wreck show a decrease in the 'bend' of the Earth's magnetic field.

On each subsequent survey line run to the east or west of the wreck the size of the anomaly is reduced, measured from the top of one peak to the bottom of the lower peak (the peak to peak value). Directly over the wreck the anomaly is 1000nT, but only 15m to the east the anomaly drops to 720nT, 15m further away it drops to 300nT, then 50nT at 45m away and finally 20nT at a horizontal distance of 60m from the wreck. In the TS plot for Line 0 the positive peak is shown before the negative peak as the survey line was run from the south to the north, but in line two the peaks are reversed as the line was run in the opposite direction. The lower-right plot shows the signal measured on a survey line run from east to west across the site, but to the south of the wreck where the field strength is strongest.

The effects on the Earth's magnetic field caused by a steel wreck are similar to those caused by smaller iron objects, but the effects are on a smaller scale. The distorted magnetic field caused by a single cannon will be the same shape but covering a much smaller area (if we ignore the effects of permanent or remanent magnetisation). The distortion around a single iron cannon may only extend a few metres around the cannon so the magnetometer must pass within that distorted field for it to be able to detect the cannon. With this in mind we can see why it is so important to get the magnetometer as close as possible to the seabed and to use a small survey line spacing when trying to detect small iron objects such as cannon and anchors.

5. Instruments, Signals and Noise

Different types of magnetometer will give different results and this needs to be considered when processing data from each type. Three types of magnetometer are commonly available for marine magnetic surveys; proton, Overhauser and caesium. Each of the three use a different method for measuring the magnetic field and the three methods give results with different properties, but essentially they should all record the same value for magnetic field strength if placed in the same magnetic field. Also, there are differences between instruments of the same type made by different manufacturers and differences between instruments made by the same manufacturer so it is important to understand the strengths and limitations of each one when analysing data from them. The main factors we need to consider are update rate and instrument noise.

Update Rate and Sample Interval

The update or sample rate of an instrument is the speed at which it can make measurements of the magnetic field:

- Proton magnetometers need time to prime their measurement sensor, known as polarizing time, and this can be in the order of one or two seconds. Added to this is a delay in making the measurement so measurements can sometimes only be given once every 2 or 3 seconds. Shorter polarizing times can be used but this reduces the sensitivity of the instrument making it less able to detect small anomalies.

- Overhauser magnetometers use a faster method of making measurements and can produce up to four measurements per second (Marine Magnetics SeaSPY). Slower update intervals will increase the sensitivity of the instrument (see below).

- Caesium magnetometers can measure up to 40 samples per second (Geometrics G882) but again the quality is improved at lower update intervals.

Figure 10 shows the effect of changing the sample rate over the same magnetic anomaly.
Graph A shows an anomaly measured using a magnetometer updating at 10Hz or 10 samples per second, we have enough samples or measurements and the shape of the anomaly is clearly represented. Graph B shows the same anomaly measured at 4Hz or 4 samples per second, here the shape of the anomaly is also quite detailed. In Graph C the sample interval has been dropped to one measurement per second and the anomaly is starting to lose its shape as only 6 measurements have been made across it. In the last graph D the samples have been further reduced to once every three seconds as produced by a proton magnetometer, here the anomaly has been reduced to a single value above the background field. This single measurement is indistinguishable from a noise spike and would be rejected as being caused by noise when processing the data.

The physical size of the object and the area covered by the magnetic anomaly it creates determines if a particular type of magnetometer will ‘see’ the anomaly. If the anomaly around an object is small then you would need an instrument with a high sample rate to be able to make enough measurements across the anomaly to detect it. For very big anomalies even proton magnetometers can detect them as enough measurements could be made to show that it is a real anomaly rather than just a noise spike.

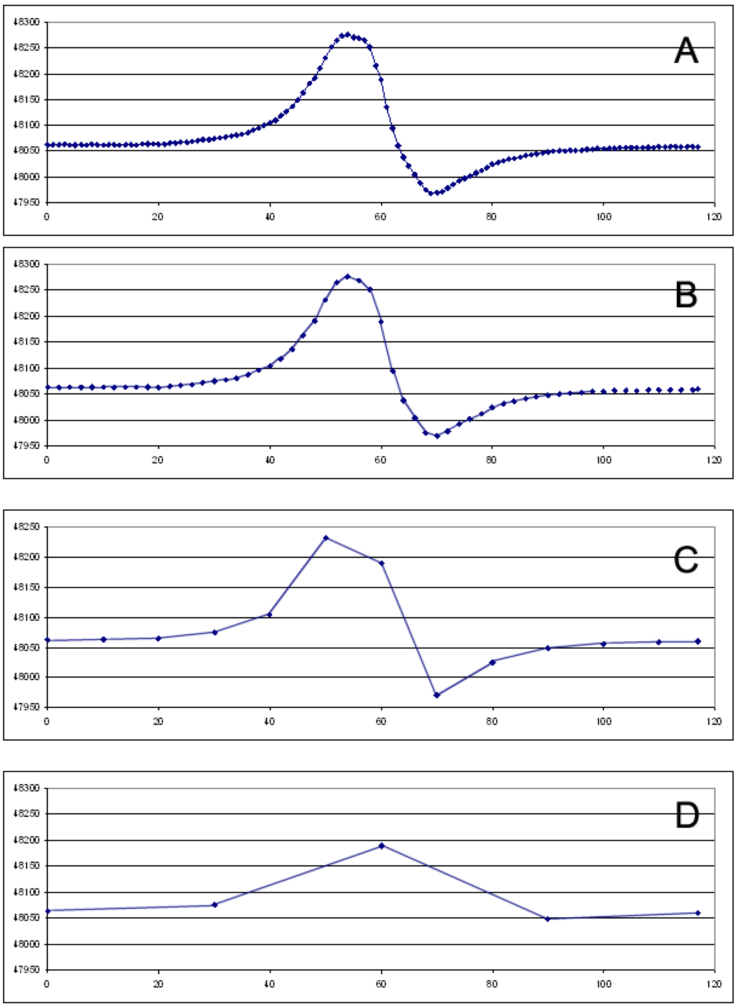


Figure 10: The effect of sample rate on the ability to record magnetic anomalies

But the rate at which measurements are made is not the only factor to consider, we also have to consider the speed at which the magnetometer moves across the seabed. A magnetometer towed behind a boat moves through the water making measurements as it goes. If it is moving at 2 metres per second and makes a measurement every second then each measurement will be 2m apart, this is known as the sample interval. If the update rate is increased to 10Hz then each measurement will be 200mm apart. If the update rate is kept at once per second but the boat speed is increased to 4 ms^{-1} then the measurements will be 4m apart.

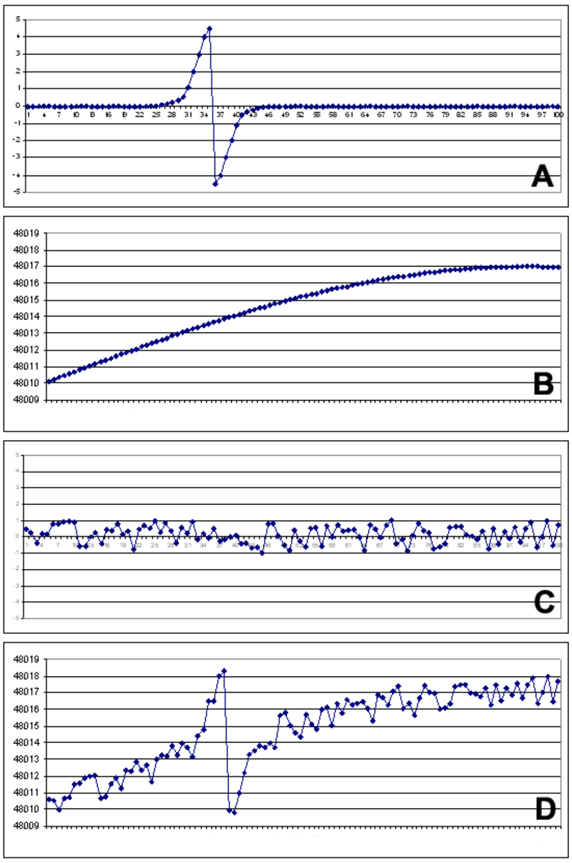
As a general rule you need a fast update rate and slow vessel speed to be able to detect smaller objects.

Noise

Noise limits how well we can make any measurement and it is important to understand how it affects measurements made by a marine magnetometer. Any instrument producing measurements will actually report a mixture of valid measurement (called signal) and unwanted measurement (called noise). It can be difficult to separate the signal we want, the measurement of the Earth’s magnetic field, from the noise that we do not want, as sometimes it is hard to tell which is which.

A typical source of unwanted noise is the noise made by the instrument itself, called instrument noise or self noise. The effect of underlying magnetic rocks and diurnal variation also change the magnetic field being measured and can be thought of as a source of noise.

Figure 11 illustrates the problem. The magnetic field measurements made over an anomaly if they could be made noise-free are shown in the upper graph A. Graph B shows the effect of underlying geology changing the background magnetic field in the area, the change is quite slow but with a large amplitude. Graph C shows the instrument noise made by the instrument itself, quite small in amplitude but with a high frequency. Graph D is what the magnetometer actually measures - the wanted signal (A) plus all the sources of noise B, C and D.



When processing this data we need to do the reverse, to try and isolate the wanted signal in the upper graph A from the measured values shown in graph D by removing the noise (C) and the effects of geology (B).

Instrument noise varies with instrument type. Often the cost of the instrument is a good indication of how noisy each instrument will be as cheaper magnetometers are usually noisier than expensive ones.

Instrument noise shows up as random variations in the measurements made by the instrument. If you record the output of a magnetometer held in a fixed position on land you can see that the measurements vary over time. How much the measurements vary is called the noise floor and it's this that limits how small an anomaly can be detected, because an anomaly smaller than the noise floor will be hidden in the noise. A magnetometer that is less noisy than another can be used to detect smaller anomalies and hence detect smaller iron objects.

Because of the way they make measurements, proton magnetometers are usually noisier than Overhauser or caesium types (Fig. 12). Overhauser and caesium magnetometers have similar instrument noise levels (Fig. 13, note difference in Y axis scale from Fig. 12).

Some of what we have called instrument noise may be caused by noise in the power supply being used to power the magnetometer. The effect of electrical noise varies with different makes and types of instrument. How each instrument and its power supply is grounded or earthed also has a significant effect on the noise level and this needs to be considered when the data is being collected.

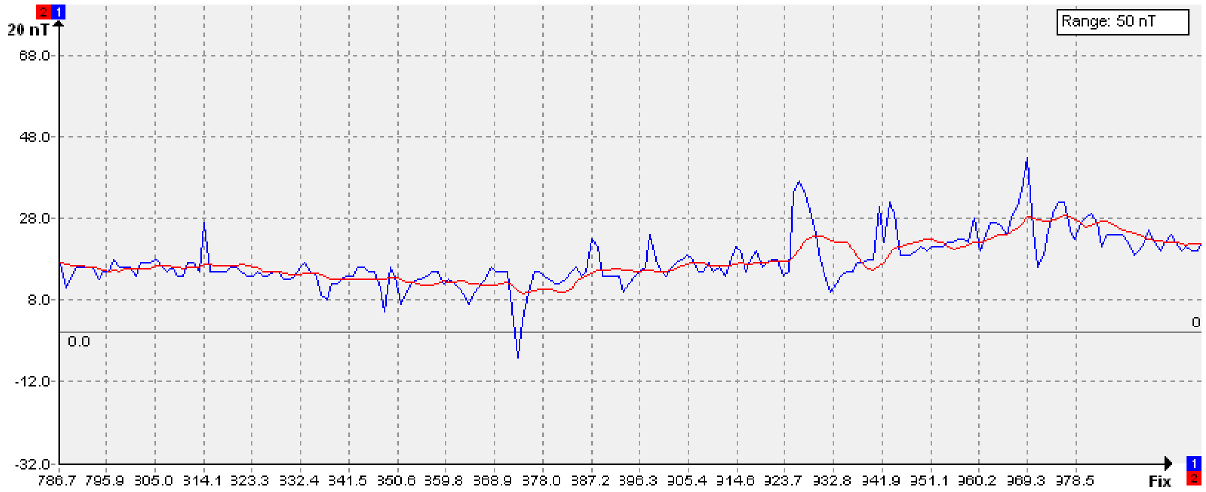


Figure 12: Proton magnetometer noise, Y scale 20 nT per division, noise 5-15nT (blue trace raw data, red trace filtered)

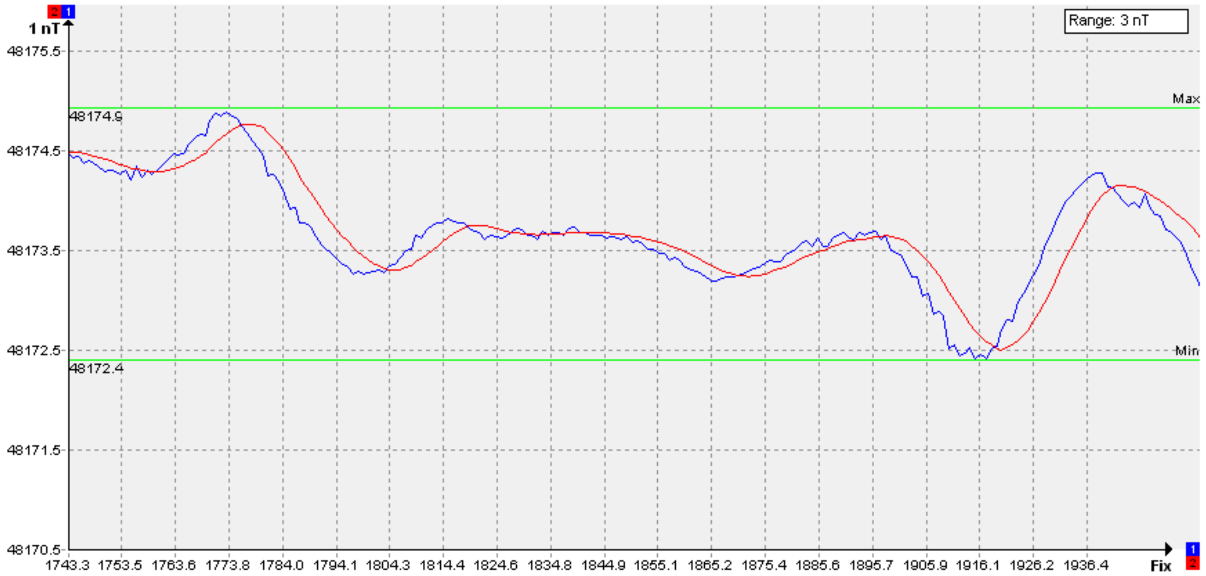


Figure 13: Caesium magnetometer, small signals in very quiet noise floor, Y scale 1 nT per division, noise 0.01nT (blue trace raw data, red trace filtered)

Wave noise has an effect on all types of magnetometer. Wave noise caused by the motion of the magnetometer within the Earth's magnetic field as it is moved by waves in the sea as the magnetometer is towed along by a boat. Wave noise is seen as a regular and periodic variation in the measurements (Fig. 14) and it is particularly noticeable in areas free of magnetic targets where the plot of the magnetic field should show a flat line.

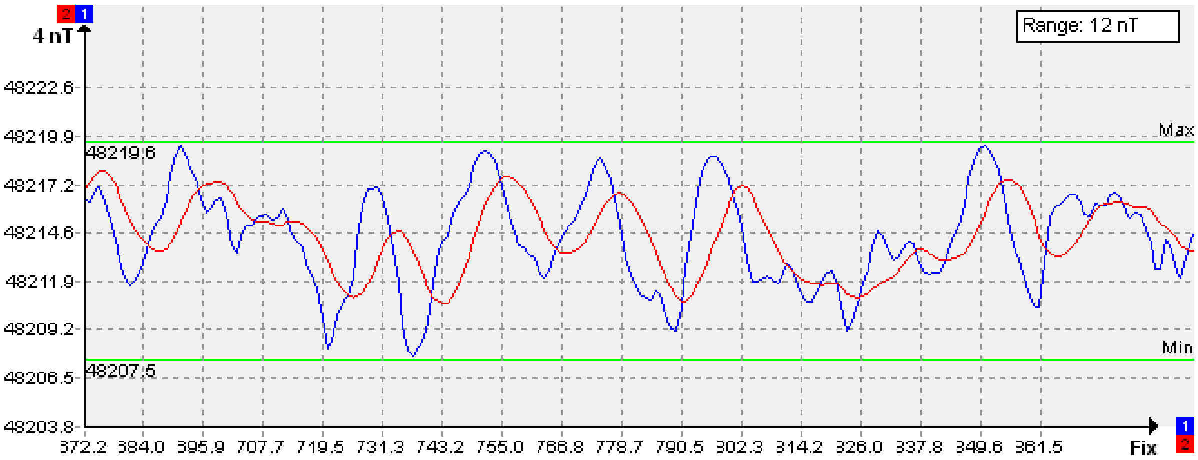


Figure 14: Caesium magnetometer data showing 10-20nT of wave noise (blue trace raw data, red trace filtered)

This type of noise is caused by vertical motion or rolling of the towfish, itself caused by wave action on the towfish or the heaving motion of the boat pulling on the magnetometer tow cable. It is particularly common on surveys where the towfish has been towed under floats on the surface and on shallow surveys where the towfish is affected by vertical movement of waves close to the surface.

Practical Data Collection

We have seen how the update rate of a magnetometer affects the sample interval and the ability to detect small objects. The noise measured by an instrument will also limit the size of anomalies that can be detected if the noise level is larger than the anomaly signal to be measured.

In practice a compromise is needed. Towing the magnetometer faster means that more ground is covered each hour making the survey more efficient, but towing slower allows smaller anomalies to be detected as the measurement samples are closer together. Increasing the update rate will increase the sample interval allowing smaller objects to be detected, but this will also increase the instrument noise for all types of magnetometer (proton, Overhauser, caesium). Increasing the sample interval will increase the noise floor so although the measurements are closer together they are also more noisy so you still can’t detect the small anomalies.

Typical surveys producing good quality magnetometer data are run at 4 knots or 2ms^{-1} with a sample interval of 4Hz (4 measurements per second) giving measurements 0.5m apart. Caesium magnetometers can be run at 10Hz to detect smaller objects but this may produce an increase in instrument noise which may be significant depending on the targets being searched for. Making measurements faster than 10Hz is not recommended for marine magnetic surveys because of the additional increase in noise.

The solution to the problem of wave noise is to ensure that the magnetometer towfish is not moving up and down or rolling as it is being towed along. For deeper surveys the unwanted movement can be limited by correct choice of tow method. For shallow surveys the tow method can be optimised but to get the best results the surveys should be done when the sea is calm and there are no waves.

6. Basic Processing

Introduction

Having understood how anomalies are formed and the limitations of the instruments used to record them we can now take some magnetometer data and identify any anomalies and the positions of their associated targets.

Often the magnetometer survey is undertaken to identify iron objects in the survey area that will then be investigated by divers or ROV. So the most important final product is a list of targets and their positions with some additional information about them.

A typical dataset will contain measurements of the magnetic field at known positions. The dataset should also include a measurement of the depth of the towfish at each point and/or the altitude of the towfish above the seabed. Often the survey boat used to collect the data will sail a regular pattern of survey lines a given distance apart. Using this information we can identify the anomalies in each survey line, estimate a position for the associated targets then estimate the mass of iron for each that would cause the measured anomaly.

The procedure for identifying targets and anomalies is the same for any data set:

- Each survey line is inspected in turn and any significant anomalies marked
- A target is associated with each anomaly except where anomalies on adjacent lines are close enough to have been caused by the same target
- A list of targets and their properties is then created
- Where possible, the target positions can be compared with the results of a side scan sonar or multibeam sonar survey so any sonar targets can be correlated with the magnetometer targets.

For each survey line the first step is to identify the anomalies so before that can happen you need to decide what will be considered to be an anomaly. Surveys are usually done for one of two reasons; either to find an object of a known size or to find all iron objects bigger than a given size. For this we need to be able to estimate the mass of iron associated with an anomaly.

Calculating Mass

There is a direct relationship between the mass of iron in a target, the distance between target and magnetometer and the size of magnetic anomaly it produces. The relationship is defined in the Hall equation.

The Hall equation relates the mass, anomaly size and distance:

$$\Delta M = \left(10 \times \frac{a}{b}\right) \times \frac{w}{(d^3)}$$

ΔM = is the anomaly size in nT
w = mass in kg
d = slant distance in metres
a/b = aspect ratio , length / width

The distance between target and the magnetometer sensor is a slant distance, the direct distance between target and magnetometer even if the magnetometer does not pass directly over the target. However, for simplicity we usually assume that the target is on the seabed and under the towfish so the slant distance can be calculated from the altitude of the magnetometer towfish above the seabed. The altitude is often calculated from measurements of water depth from an echo sounder and the depth of the towfish measured by the towfish itself.

The aspect ratio is a factor that can be included in the calculation to overcome differences noted in the mass predicted by the equation and the actual mass of iron causing the anomaly. Why the predicted and actual mass of iron can be different is the subject of research by the SHIPS Project with CISMAS and hydrography students at Plymouth University.

However, for the majority of situations the aspect ratio can simply be set to a value of 1.

Rearranging we get:

$$Mass\ (kg) = \left(\Delta M \div \left(\frac{a}{b}\right) \div 10\right) \times d^3$$

Example:

For a measured magnetic anomaly of 13nT with a towfish altitude of 20m above the seabed and using an aspect ratio of 1 we get:

$$\begin{aligned} \text{Mass (kg)} &= (13\text{nT} / 1 / 10) \times (20)^3 \\ &= 1.3 \times 8000 \\ &= 10400\text{kg or } 10.4 \text{ tonnes} \end{aligned}$$

Note that this estimate of mass assumes that the object is lying on the seabed and directly under the towfish. If the object is buried or to one side of the survey line then it will actually be further away from the towfish and the calculated mass will be underestimated.

We can also calculate how close the towfish has to be to detect objects of different sizes. If we assume that the smallest anomaly we can reliably detect is 5nT then the distances are:

Example target	**Mass**	**Minimum detection distance (5 nT anomaly)**
20lb round shot	9 kg	2.7m
32lb round shot	14 kg	3m
Small anchor	100 kg	6m
Small anchor	500 kg	10m
Small Iron gun (9lb)	1.25 tonne	14m
Medium Iron gun (18lb)	2 tonne	16m
Large Iron gun (42lb)	3.25 tonne	19m
Iron ballast	10 tonne	27m
Small iron wreck	100 tonne	58m
Iron wreck	1000 tonne	126m

Table 1: Minimum detection distances

So this means that you need to get the magnetometer towfish within 3m of a single 32 pdr cannonball to be able to detect it. Towing the magnetometer only 3m above the seabed may be unsafe as the chance of hitting something is high. We can reliably tow the magnetometer at 6m above the seabed, so the smallest object we can reliably detect is 500 kg.

Problems with the Hall equation

Practical tests on land using magnetometers over selected iron objects has shown that the Hall equation does not always give an accurate prediction of the mass of a target. Field trials using targets detected during a magnetometer survey then identified by divers shows that some targets have a good prediction of mass while others can be wrong by up to a factor of three, so the Hall equation can be used as an approximate indicator of mass but not a precise one.

Tests on a number of cannons of the same type on a shipwreck site showed that they had magnetic fields of different sizes and shapes. One of the reasons that there are differences between predicted and actual mass may be because of the magnetisation of the object itself, known as remanent or permanent magnetisation. The remanent magnetisation is the magnetic field that an object has if the Earth’s magnetic field was not present. The magnetic field around an object is the sum of the magnetic field induced in it by the Earth’s magnetic field plus any remanent field the object has. The remanent field makes the object, say a cannon or an anchor, behave like a magnet with a north and a south pole. If the remanent field is aligned with the Earth’s magnetic field then the effects will add up making the field distortion measured by the magnetometer larger than expected. If the alignment is opposite then the remanent field will counteract some of the induced field and make the signal recorded by the magnetometer smaller than expected. The alignment of the remanent field of an object will vary according to a number of factors, including how the object was aligned in the Earth’s field when it was made. Tests on this idea are still being done so the results are not yet published.

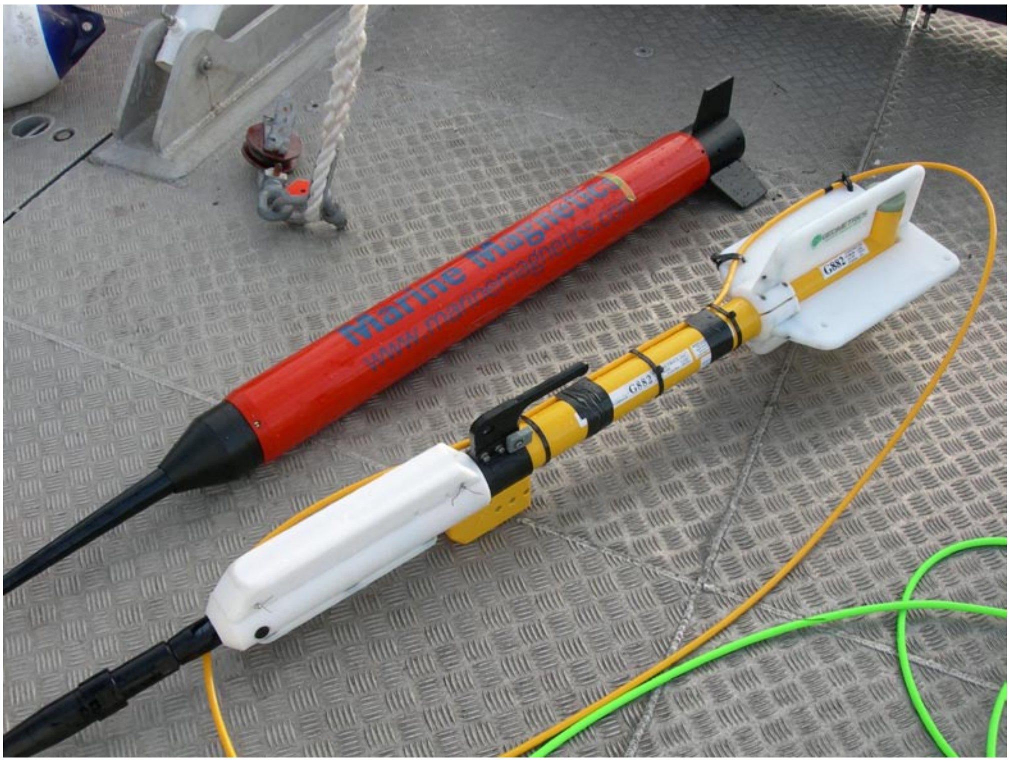


Figure 15: Testing two types of magnetometer; Geometrics G882 caesium vs. Marine Magnetics SeaSPY Overhauser

Survey Strategies

Method 1 - Finding a Single Target

For some surveys where a single large object is to be found the largest anomaly in that area will be the one being searched for. If the survey area is contaminated with modern debris then this may not be the case and a better strategy is needed.

To be able to recognise the target we are looking for we need to estimate the size and shape of the magnetic anomaly that would be created by our object if it were within the survey area.

Knowing about the object itself we can estimate the mass of iron and estimate if it is contained in a small area like an intact wreck or more widely spread like a scattered wreck site. Using a typical value for the towfish depth, water depth and runline spacing we can calculate the size of magnetic anomaly that would be created by our estimated target mass of iron. The anomaly should have a maximum and minimum value based on best case and worst case scenarios that include uncertainties in towfish height and runline width as well as a factor of three variation for uncertainties in the mass calculation. The range of sizes for the magnetic anomaly can then be used to eliminate other anomalies in the dataset that are either too large or too small. The estimate of the shape of the anomaly can also be factored in as a scattered wreck site is likely to be seen as a number of smaller anomalies rather than one single large anomaly.

Method 2 - Identifying all Targets

The alternative strategy is to identify all the magnetometer targets in a given area that are bigger than a given size. For this we need to work out what is the smallest mass of iron target that we can detect, known as the minimum detectable target, or MDT.

How small an anomaly we can detect is dependent on the amount of noise in the data. The amount of noise depends on the magnetometer used, how it is powered and how it is towed. To be detected, an anomaly has to be bigger in size than the background noise so smaller anomalies will be found if the background noise is smaller. The amount of noise recorded by the instrument may vary across the survey area as it can be dependent on the sea state which may vary over time or as the tide changes.

The smallest mass of iron we can detect can be calculated using the Hall equation mentioned earlier. This relates the mass of iron to the distance between target and magnetometer and the smallest detectable anomaly size. The maximum distance from towfish to target is a function of the runline separation and the maximum altitude of the towfish. Using this and the smallest detectable anomaly value we can work out the smallest mass of iron that we can identify at any point in the survey area. If one part of the area has deeper water than another but the towfish is maintained at the same depth, the distance to target will be greater for the deep area so the smallest mass that can be detected will be larger.

Calculating the MDT is a useful exercise because you may be surprised at the size of the smallest mass that can be detected as it is often larger than you would like. It is actually quite difficult to detect a single iron object smaller than 500kg with a standard towed magnetometer as for this to happen the towfish needs to be 6m or less above the seabed. It is often thought by inexperienced operators that the magnetometer will detect objects much smaller than it can in reality. Worse still, what the magnetometer can reliably detect may not be considered at all. There are some published reports on marine magnetometer surveys undertaken for archaeology projects where the target being searched for could never have been detected with the equipment or deployment method used.

Calculating the minimum detectable target is discussed in the section on Further Processing.

Identifying Anomalies and Targets

Knowing what can be considered to be a valid anomaly we can now identify them within the data using a time-series (TS) plot. The TS plot shows the variation in measurements over time with the most recent measurements on the right side of the plot and previous ones to the left.

We have seen that the shape of the anomaly varies with target characteristics, the direction of tow and where the towfish passes through the distorted magnetic field. Any change in the magnetic field that is sufficiently larger than the noise floor can be considered to be an anomaly, however some of the anomalies may be caused by geology and can be discarded. Anomalies caused by geology are often larger in area than man-made anomalies of the same field strength and may not include a negative part where the magnetic field strength is less.

We need to record some basic information about each anomaly. Most important is the estimated position for the target that caused the anomaly and this is dependent on the anomaly shape. For simple ‘monopole’ (single peak, up or down) anomalies the position is taken to be the top or bottom of the peak (Fig 16a). For ‘dipole’ (dual peak, one peak up and one down) anomalies the position is taken to be between the high and low peak where the signal crosses from one to the other, see Fig 16b.

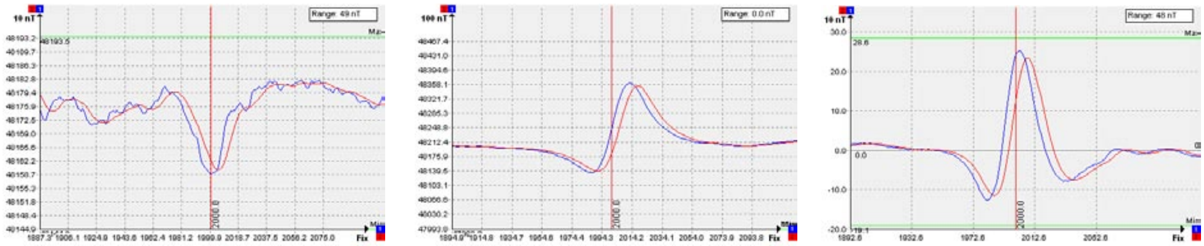


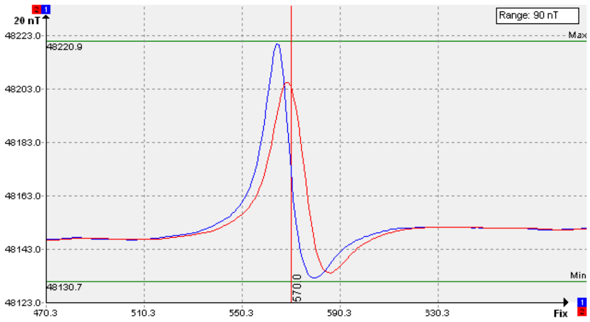
Figure 16 a-c: Position relative to anomaly shape, red vertical line marks the position of the target

For more complex shapes such as 16c the position is taken to be the middle of the anomaly. Difficulties can occur where the magnetic fields from two objects overlap and produce a distorted field that is the combination of both. This usually only occurs with smaller objects that are close together so a single position in the middle of the anomaly is usually sufficient to locate both objects when they are investigated later on.

For the mass calculation we also need to record the altitude of the towfish above the seabed, either from direct measurement from an altimeter on the towfish or calculated from the towfish depth and the depth measured by an echo sounder at that point. If no bathymetry or seabed depth measurements are available then the seabed depth can be taken from a chart so long as it is corrected for the height of tide at the time the survey was done.

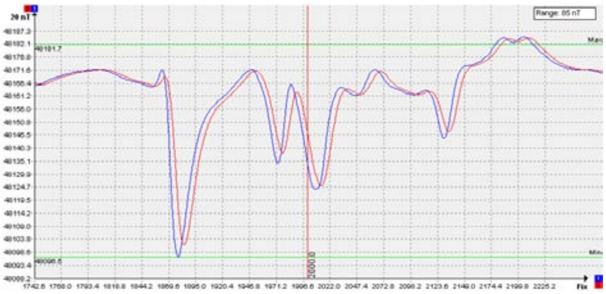
Experience provides the clues to finding suitable targets in different environments, particularly when differentiating a geological feature from a man-made one. Much can be gained from comparing data from different parts of the survey area and looking for anomalies that are different from the others within that area. Ground truthing targets early on in the work can also help identify signatures of different types of target so you can, for example, more easily tell a collection of dumped trawl gear from a small wooden shipwreck with iron fittings.

Example anomaly shapes are given in figures 17-20 below:



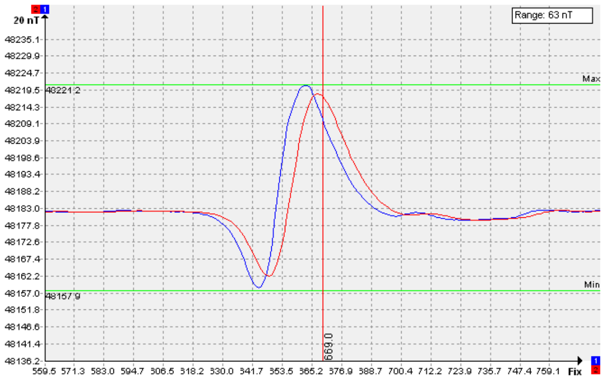
This anomaly shows a big positive peak and a small negative peak that are both much larger than the background noise level. The noise level can be seen by looking at the trace away from the anomaly on either side of the plot, the noise level is too small to see. The position of the target associated with the anomaly is shown at the vertical red line.

Figure 17: A 10 ton anchor at 10m towfish altitude, from south to north



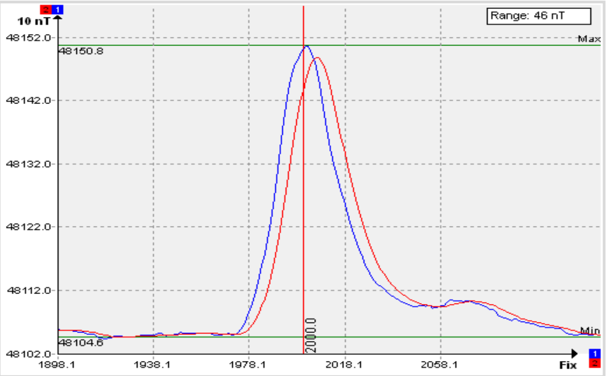
Steel cables often show up as a monopole with a large anomaly size, larger than you would expect for so small amount of steel. Each negative peak in this plot is caused by a separate cable.

Figure 18: Cables at 5m towfish altitude, run north to south



A 2m long iron cannon will produce a large 63nT anomaly but only if the magnetometer is towed close to it, 5m away in this case. The anomaly is a bipole with both positive and negative peaks and again much larger than the background noise level. The magnetometer was towed in a north-south direction across the cannon so both positive and negative peaks are seen.

Figure 19: A 2m long iron cannon at a towfish altitude of 5m, north to south



This 46nT anomaly was created by towing the magnetometer 10m above a 16ft long iron anchor. The tow was east to west and across the positive peak of the anchor's magnetic field.

Figure 20: Small iron Admiralty longshanks anchor at a towfish altitude of 10m

Using a chart

Processing using time-series plots alone has its limitations as it does not give a good idea of where anomalies are in relation to one another. The same survey data can be shown on a chart as a series of track lines showing the path of the magnetometer in a two-dimensional plan view. Colouring the track lines according to the measured magnetic field allows us to visualise the same data in a different way.

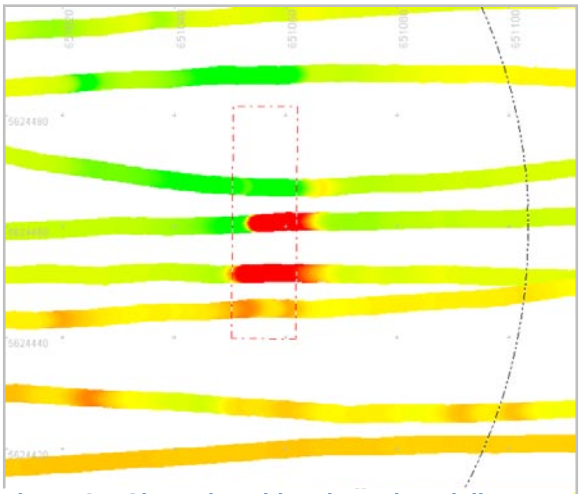


Figure 21: Chart plot with coloured track lines

In figure 21 the red areas show regions of increased magnetic field strength, the green areas show regions of reduced field strength and the yellow areas show the undistorted or background field. Using a chart we can see more clearly how the anomalies relate to one another and also see if any anomalies have been detected on multiple lines.

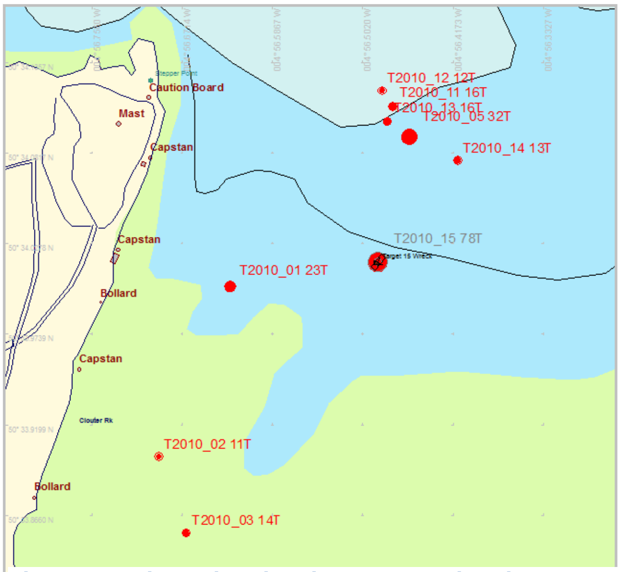


Figure 22: Chart plot showing target point size proportional to target estimated mass in tonnes

Often the required result of a survey is simply a list of targets that need to be investigated. A chart showing the locations of the targets gives a better idea of how the targets are grouped and whether there is any pattern to the distribution, such as caused by a debris trail from a shipwreck.

The size of the anomalies can also provide useful information. We can show targets as points with the size of the point representing the size of the anomaly in nT, so the larger anomalies will show up more easily than the smaller ones, but groups of targets can still be seen (Fig. 22).

Using a combination of time-series plot and chart you should be able to identify the significant targets within the survey area. This is often an iterative process where you start with the time-series plot, mark those targets on a chart, which then suggests other areas in the data where you could look for more targets. This can be helpful when deciding whether a small anomaly is really an anomaly or just noise as its position may correlate with other anomalies or a debris trail.

Other features we can add to the chart to aid processing include:

- Including the coastline gives a much better understanding of scale and how the targets relate to a shoreline
- Water depth contours taken from a chart show the depth of each target
- Including known wrecks, buoys and cables may help identify targets that are caused by a known feature
- Including the type of seabed material may help with target location as targets on rock are likely to be on the seabed but targets on mud or sand may be buried
- Results of previous magnetometer surveys can be added as many of the targets will correlate with previous ones. Targets that match give confidence that the target is repeatable but ones that do not could be noise interpreted as an anomaly.
- The results of other surveys can be included. Side scan sonar, multibeam and sub-bottom profiler targets can be included as targets on one survey may show up on another.
- Plotting the targets over a side scan sonar or multibeam mosaic can help identify targets without the need for further investigation as the target may be visible on the mosaic. Targets that appear on the sonar mosaic without an associated magnetometer target suggest that the sonar target is not made of iron.

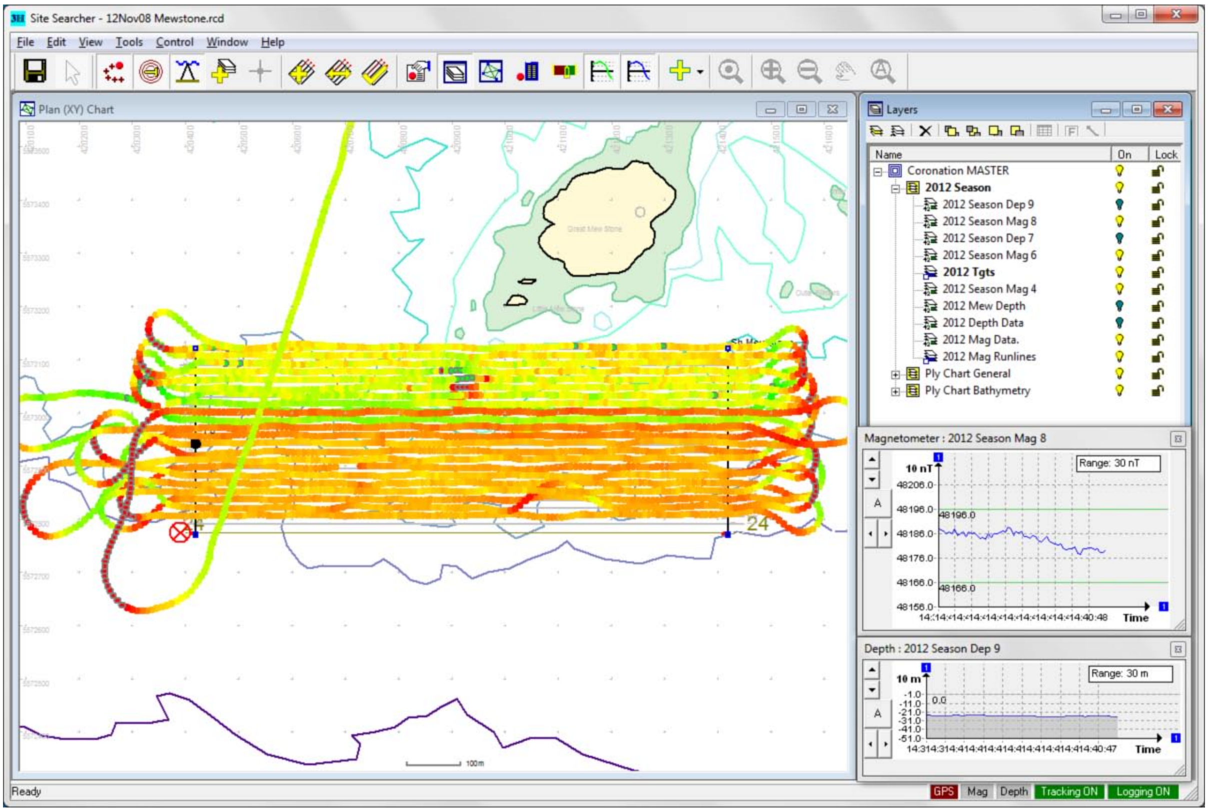


Figure 23: Site Searcher screen with the chart showing coastline, bathymetry, targets and magnetometer track lines coloured by field strength

7. Further Processing

Introduction

Basic processing of magnetometer data involves identifying anomalies, plotting the positions of targets from those anomalies and estimating the mass of iron in the target. Further processing of the magnetometer data can be done to get better results or extract more information. This section discusses how the anomalies we want can be identified within a number of different noise sources that affect magnetometer surveys.

Dealing with Spikes and Dropout

The ability to detect the smallest magnetic anomalies is usually limited by noise in the measurements. Some noise can be removed by filtering but it is always better to minimise the noise recorded during the survey rather than having to deal with it in post-processing.

Spikes in the data are short duration jumps in the measurements that are considerably bigger or smaller in amplitude than the background magnetic field value. Spikes may be caused by a number of sources including electrical noise and excessive motion of the magnetometer towfish. Dropout also causes spikes in the data and this is caused by intermittent communications with the instrument (Fig. 24).

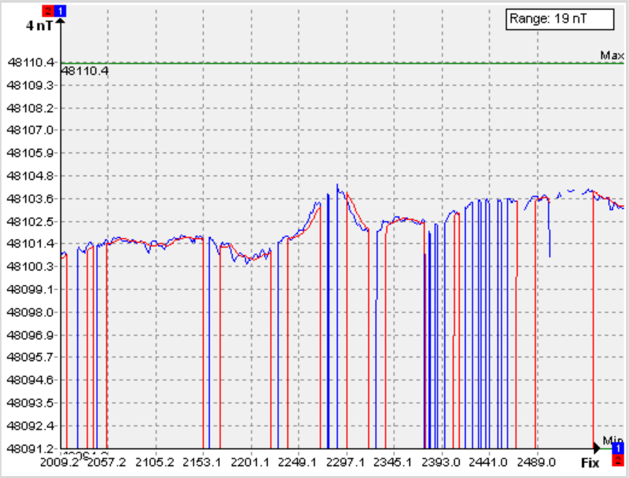


Figure 24: Time series plot showing dropout

Removing the spikes, or ‘despiking’ can be done by removing any measurement larger or smaller than some given value. This can only be used reliably when the spikes are much bigger in value than the change in magnetic field across the site. A smarter method involves applying a gate or window around the average of the last few measurements and rejecting any subsequent measurements outside this ‘gate’. Here the rejection value ‘tracks’ the average value of the measurements so a narrower rejection range can be used. Care is needed in ensuring that despiking does not actually remove useful anomalies.

Towfish Turns

Magnetometer data is likely to be unreliable when the vessel, and thus the towfish, is turning sharply. The measurements from the instrument may increase or decrease sharply as the towfish turns but resume the same background level when the track straightens out (Fig. 25). In some cases the data gets very noisy during the turn with large spikes being recorded. The problem may be caused by wobble in the towfish as it turns because the data is usually affected less for wider turns, whilst rougher sea states can make the problem worse.

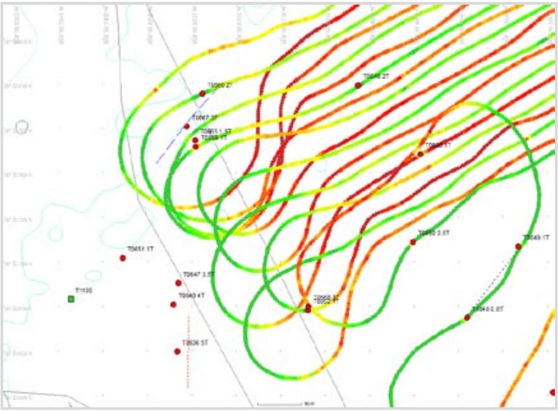


Figure 25: Chart plot showing change of magnetic signal during turns

Care is needed when processing data showing these symptoms as any anomalies seen in the turn may be caused by noise and should be discarded.

Other Contamination

A marine magnetometer is effectively an omni-directional sensor so a steel ship on the surface that passes the magnetometer during a survey will affect the magnetic measurements and will show up as an anomaly. The same applies to fixed magnetic features such as navigation buoys and power cables. During data collection it is important to note when these events occur in the survey log so their effects can be removed from the data during post-processing, otherwise a navigation buoy or passing boat could be identified as a significant target.

Dealing with the Effects of Geology

Some rock formations are magnetic, particularly volcanic rock or rock with a high iron content. If the rocks that form the seabed in the survey area are magnetic then they will affect the results of the survey as the magnetometer will detect their influence on the Earth's magnetic field. In many parts of the world the effects will be small in amplitude and can be ignored. In areas where the effects can be noticed the effect on the magnetic field may be gradual giving one end of the survey area a higher background field than the other. But in strongly magnetic areas the effect of underlying geology can even be enough to mask anomalies from man-made objects.

Fortunately, in most cases the shape of anomalies created by underlying magnetic geology are different from those created by man-made objects. Man-made objects are usually smaller in physical size so produce anomalies that are correspondingly small in length and width. Geological anomalies are often much broader as they cover a larger area and have a small amplitude signal. Sometimes they show up as a ridge of magnetic disturbance running across the site as shown in figure 26:

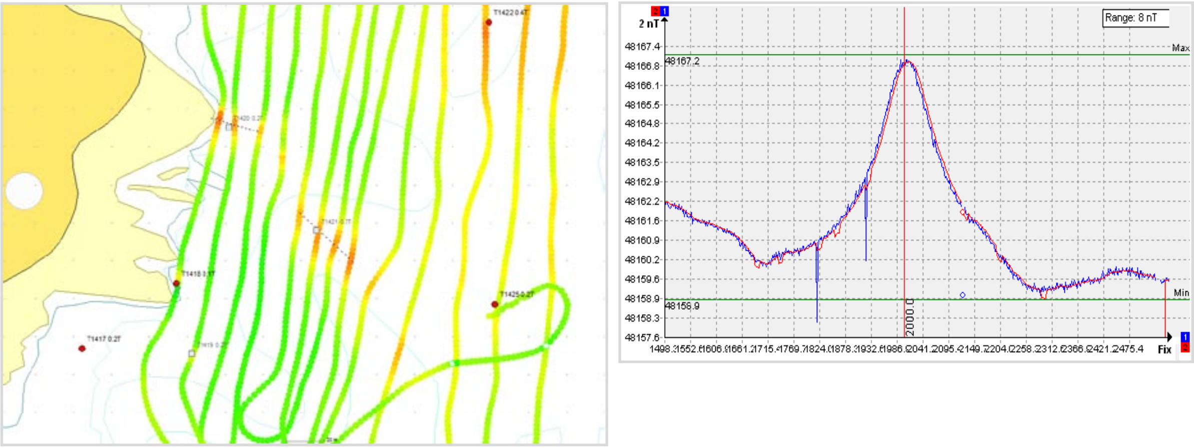


Figure 26: Magnetic ridge caused by underlying geology

Note that the magnetic rock anomaly shows up as a positive only distortion in the magnetic field and it does not have an associated area of negative field strength as a mad-made iron object would.

When processing, we need to be able to tell the difference between the anomalies we want and the background magnetic field. The background field is the Earth's own magnetic field distorted by the underlying geology. This is often known as separating the regional field (earth and geology) from the residual field (anomalies plus noise). Where the effects of underlying geology are small they can often be ignored and the data processed as normal. If the effects are noticeable then the data can still be processed by hand simply by ignoring any large scale changes in the background magnetic field. If we do need to remove the effects of geology then we can use filters to do this, similar in principle to the filters that are used in an audio amplifier to alter the level of treble and bass.

We use the term 'wavenumber' to describe the way the magnetic field changes across the site, wavenumber is similar to wavelength but describes how the magnetic field changes with distance rather than time. Geological anomalies usually have a long wavenumber (similar to a long wavelength) and man-made objects usually have a short wavenumber (or wavelength).   We can use this difference to create a high-pass filter that removes the long wavenumber anomalies we do not want but keep the high wavenumber anomalies created by man-made objects. This also removes the absolute magnetic field value (around 50,000nT in the UK) so the filtered values show anomalies on a time-series plot going above and below a zero mean value. Care has to be taken to ensure that the filtering process does not remove any part of the wanted signal otherwise some real anomalies will not be identified.

Dealing with Diurnal Variation

Diurnal variation is the change in the background magnetic field caused by the Earth's rotation relative to the sun. The change is slow but can produce differences over a day of tens of nanoTeslas, often larger in size than the smallest anomalies being searched for.

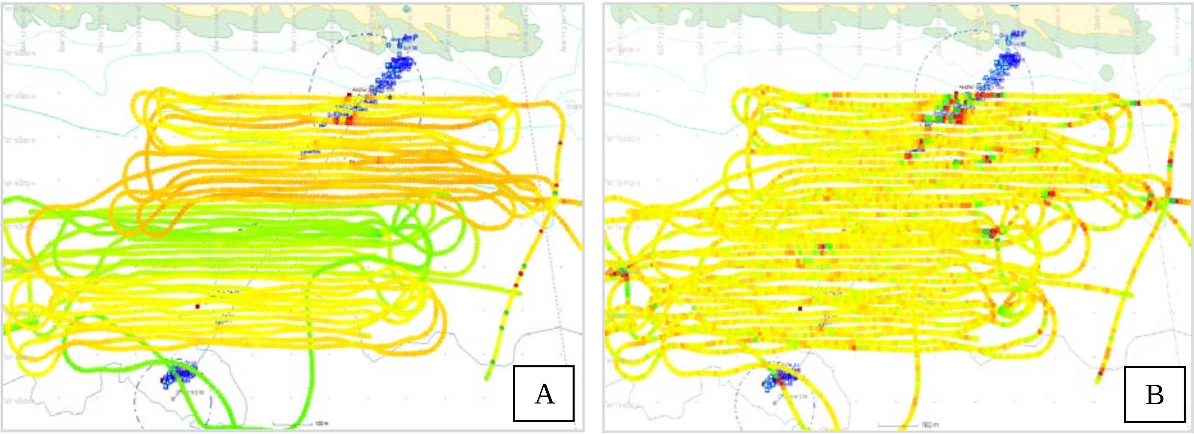


Figure 27: Three survey areas done at different times showing the effect of diurnal variation (A), and the improvement in the data once the effect had been removed (B)

The effect is particularly noticeable when parts of a survey are done at different times of the day as the level of the background field can be significantly different, figure 27A shows the survey lines grouped in three horizontal colour bands from three separate magnetometer surveys done on different days and at different times. Figure 27B shows the same data filtered to remove the effects of diurnal variation; notice that the smaller red and green anomalies are now much more easily seen. The 'tiger stripes' in Fig. 27 B are caused by wave noise which is described below.

The effect of diurnal variation can be removed a number of ways:

- Filter the data using a high pass filter as used for removing the effects of geology.
- Or each survey line can be shifted up or down to an arbitrary level so the average value for each line is the same. This can only be used in areas not affected by magnetic rocks and where the change in background field over the whole site is small.
- An additional cross line of magnetometer data can be used, this is a line run across the survey area at right angles to the main survey lines. The values of data points on each survey line can be shifted up or down so that the signal values are the same where the cross line and survey line meet. A better answer can be obtained if more than one cross line is recorded and used to compute the shift for each survey line.
- A second magnetometer set up at a fixed position nearby can be used to record the change in magnetic field over time during the survey operation. The changes in the background field caused by diurnal variation will affect both the fixed and towed magnetometer so the logged data can be used to correct the data from the towed magnetometer.
- Information from a magnetic observatory can be used in place of a dedicated reference station so long as the observatory is close to the survey area.

Levelling

Sometimes the background field measured by the magnetometer can change according to the line direction which makes all the measurements from lines run in one direction slightly higher than the measurements collected in the other (Fig. 28). This may be caused by the towfish being too close to the towing vessel when working in shallow water.

Again an additional cross line of magnetometer data can be used to correct the data, this is a line run at 90° to the main survey lines. In processing, the values of data points on each survey line are shifted up or down so that the signal values are the same where the cross line and survey line meet. A better answer can be obtained if more than one cross line is recorded and used to compute the shift for each survey line.

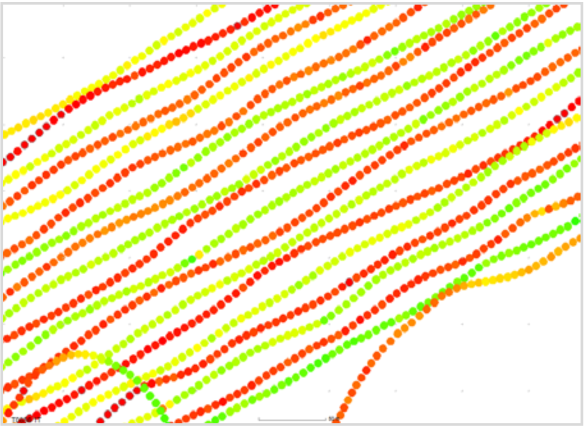


Figure 28: Lines 40nT different in absolute value, alternate lines run in different directions

Wave Noise

Wave noise or swell noise is created by vertical motion of the magnetometer in the water column and like other sources of noise it is better to avoid recording it rather than trying to remove it from the recorded data. Wave noise shows up as a regular, periodic change in the amplitude of the magnetic signal (Fig. 29). With a long, slow swell the wavelength (or more correctly the wavenumber) of the noise is correspondingly low and in some cases it can be reduced by high pass filtering. Wave noise from a choppy sea may unfortunately have a similar wavenumber to small magnetic anomalies so filtering out the wave noise will also remove the legitimate anomalies being searched for. As it often cannot be removed the wave noise effectively increases the noise floor value, masking small anomalies and making processing much more difficult to do.

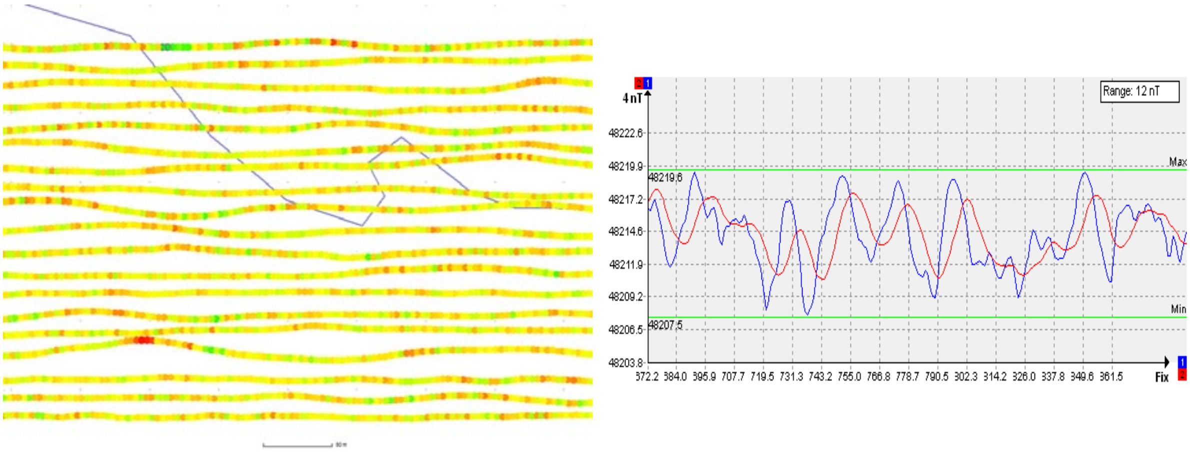


Figure 29: Wave noise causing 'tiger stripes' on the chart plot

As it can be difficult to remove the effects of wave motion it is far better to collect magnetic survey data on calm days and to whatever is possible to reduce the effect of wave motion when towing the magnetometer.

Calculating the Minimum Detectable Target

The minimum detectable target is the smallest anomaly that could be detected during the survey. This is an important piece of information as by calculating the MDT in advance of doing a survey you can determine if the target you are looking for can actually be detected.

The Hall equation relates anomaly size and distance between target and magnetometer to the mass of iron in the target. To calculate the MDT for any point in the survey area we need to know the smallest anomaly that could be detected and the furthest distance a target could be from the towfish.

We can calculate the maximum distance that a target will be away from the towfish from the towfish height above the seabed and the runline spacing. The maximum distance is the slant distance from the towfish to half way across the runline spacing, as beyond this distance from the towfish the anomaly will be closer on the next line across. So:

$$\text{Max distance} = \text{sqrt}\ (\ (\text{runline spacing} / 2)^2 + \text{altitude}^2)$$

In Figure 30 the maximum detection distance is the distance between the towfish and point B:

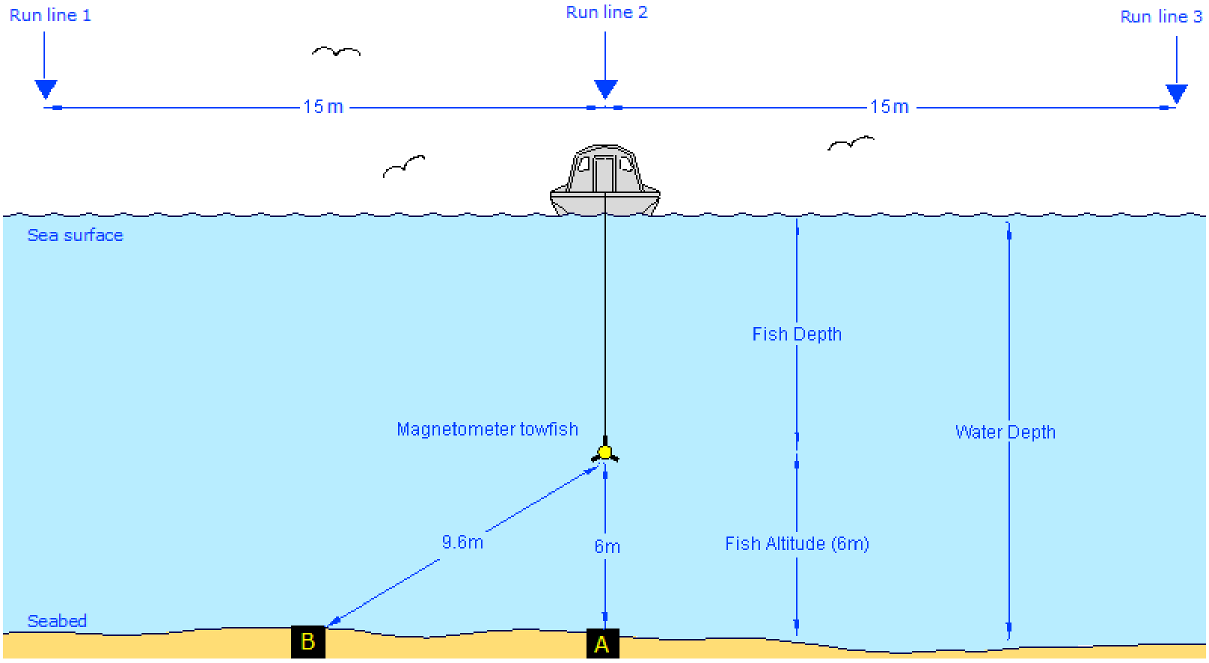
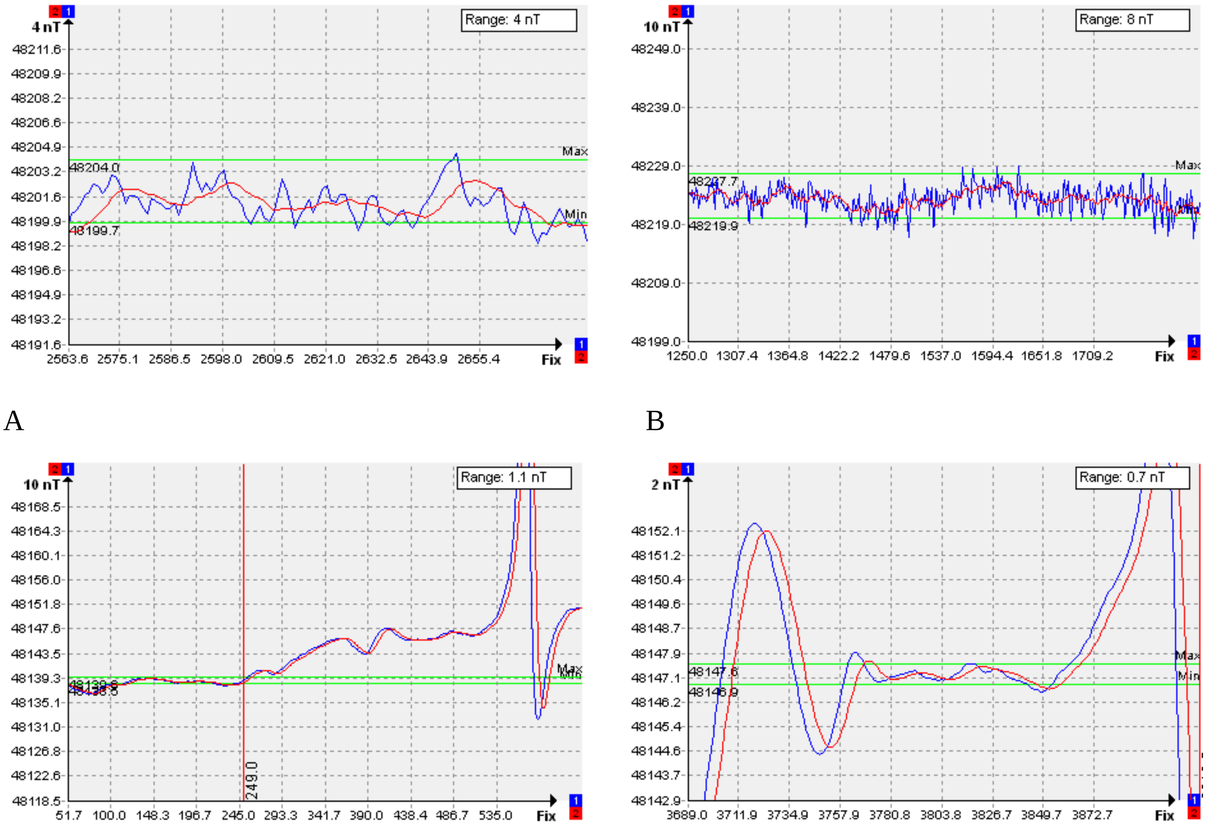


Figure 30: Maximum detection distance (Kevin Camidge)

The actual height of the towfish during the survey will not be the same as the planned height, so the actual MDT for each part of the survey area will be different to the planned value. If one part of the area has deeper water than another but the towfish is maintained at the same depth, the distance to target will be greater for the deep area so the smallest mass that can be detected will be larger. Getting the towfish close to the seabed can be difficult so often the slant distance is larger, so the actual MDT is larger too.

The next information we need is the size of the smallest anomaly we could detect and this is dependent on the amount of noise in the measurements. The amount of noise depends on the magnetometer used, how it is powered and how it is towed. To be detected, an anomaly has to be bigger in size than the background noise so smaller anomalies will be found if the background noise is smaller. To be a legitimate anomaly rather than noise the anomaly's 'wiggle' on the graph needs to look significantly different to the noise around it. In practice the signal typically has to be two to three times the amplitude of the background noise (noise floor).

The expected background noise for a planned survey can be determined from data collected on previous surveys. The level of background noise can be measured in a part of the data where no anomalies can be seen and in an area where the noise is the quietest, the value used is the average amplitude measured from the upper peak to the lower peak.



A

B

C

D

Figure 31: TS Plots A to D of background noise levels

Figure 31 above shows the noise measured on four different surveys. Figure 31A shows data from a Geometrics 882 caesium magnetometer towed in shallow water where the towfish was being moved around by waves so the noise floor is 4nT measured peak to peak, this would give a minimum detectable anomaly of 8 to 12nT. Figure 31B is similar with a caesium magnetometer towed on the surface in 5m water depth and the noise floor is larger at 8nT, giving a minimum detectable anomaly of 16 to 24nT. Figures 31C and 31D show the opposite case, a caesium magnetometer towed much deeper in quiet water so the resulting noise floor is around 0.5nT, with a resulting minimum anomaly of just 1 to 1.5nT. All of these datasets were collected using the same equipment, same vessel and same power supply so the variation is due to the towing arrangement and the sea state.

So for survey planning we should consider how the equipment is deployed and its effect on the noise floor, and hence its effect on the smallest anomaly that can be detected. For a typical survey in water deeper than 10m an estimated noise floor of 1nT could be used giving a smallest detectable anomaly size of 2 to 3nT. In shallow water where the towfish is on the surface and affected by movement by waves the noise floor can be 4 to 8nT, giving a smallest detectable anomaly size of 12 to 24nT.

Suppressing Noise
Multiple towed magnetometers can be used either as a gradiometer to measure the field gradient between the two sensors or by differential processing of their measurements. This has the effect of suppressing noise that is affecting both sensors at the same time, such as noise in the background field, so these methods may be useful when looking for the smallest targets.

In practice other effects become noticeable. Where the instrument noise is very low such as in figures 31C and 31D the small variations in background field become noticeable and the limit on the ability to detect small anomalies is now dependant on the size of those variations. Also, the amount of noise recorded by the magnetometer may vary across the survey area as it may be dependent on the sea state, which itself may vary over time or as the tide changes.

Having chosen the minimum detectable anomaly size for planning or for calculating the MDT achieved during the survey we can move on to calculating the MDT value itself by putting the values in to the Hall equation (see Section 6 Basic Processing).

Survey Specification for Underwater Cultural Heritage

Using the idea of a minimum detectable target (MDT) we can calculate the survey specification that would be required to detect a target of a given size on any marine magnetic survey. The specification defines how the data should be collected so the smallest target can be detected. The MDT is calculated from the runline spacing, towfish altitude and the smallest detectable anomaly, so each of these needs to be included in any survey specification.

The specification for any marine geophysical survey is a compromise between the need to detect the smallest targets, operational constraints and economics. If we set the smallest target we want to detect to be a large mass of iron then we can relax the survey specification, use wider runline spacing or tow the magnetometer further from the seabed. This will make the survey both quicker and cheaper to complete and make it easier to accomplish, but this will miss any targets smaller than the large mass of iron. Alternatively, if we select a minimum target size that is too small then the survey may not be possible to complete as the runline spacing will be too small or the towfish will have to be unacceptably close to the seabed. The choice of minimum target size also depends on what targets are being searched for; if you are only looking for large iron ships then a small runline spacing may not be required but if you are looking for a scatter of iron cannons then the smallest achievable line spacing is needed. Economics also plays a part; high resolution surveys are more expensive because narrow line spacing requires more lines to be run to cover a given area, plus the need to reduce instrument noise often requires calm weather so more down time would have to be paid for.

The first factor to consider is the runline spacing. During magnetometer survey work at Plymouth University for the SHIPS Project using a 12m long boat we can reliably run survey lines 15m apart or even 10m apart in calm weather. Larger boats are harder to steer so precisely so a wider line spacing is all that can be achieved, but smaller boats may be able to run lines just 5m apart. Achieving close line spacing also requires the use of a high quality surface positioning system as 5m survey line spacing would be unreliable if positioned with a typical WAAS enabled GPS giving 4m precision. When using a larger vessel, the wider line spacing that can reliably be achieved has to be factored in to the MDT calculation which will increase the size of the smallest target that can be detected. For example, with a runline spacing of 15m and typical values for towfish altitude and noise floor a 0.5 tonne target can be detected, but increasing the spacing to 30m increases the MDT to 2 tonnes and increasing further to a spacing of 50m increases the MDT to 8 tonnes.

It can be difficult to get the magnetometer towfish close enough to the seabed. None of the commercially available magnetometers will tow as deep as a typical side scan sonar of equivalent size with the same length of tow cable deployed. To get the towfish deeper requires more tow cable to be paid out behind the survey boat which makes turning more difficult and increases the uncertainty in the towfish position. A slower boat speed will also make the towfish fly deeper but this can make the survey vessel more difficult to steer and increases the time the survey takes to complete. Additional weights and depressors have been used to help the towfish fly deeper but each method has its problems. Towing the magnetometer behind a side scan sonar does enable both to tow deeper and many good quality side scan sonar systems have the capability to do this. One method that has been tried recently to obtain the optimum altitude and runline spacing is to tow the magnetometer behind an autonomous underwater vehicle (AUV). An AUV has a very precise altitude and position control so can run survey lines more precisely than can be achieved with a tow vessel especially over a seabed that is not flat. This also has the advantage of minimising motion induced noise so gives magnetometer data of extremely high quality (Hrvoic 2014). The down side to this method is the cost involved in obtaining and deploying the AUV and the difficulties of integrating the magnetometer to it.

In depths shallower than 40m it should be possible to maintain a towfish altitude of 6m above the seabed so long as the seabed is flat or gently sloping. In areas where the water depth changes dramatically then the safety of the towfish is a factor and a higher tow altitude may be required to avoid the towfish hitting the seabed. In this case the additional altitude has to be factored in to the MDT calculation which will increase the size of the smallest target that can reliably be detected.

The third factor is the smallest magnetic anomaly that can be identified. The smallest anomaly that can reliably be detected is 2 to 3 times the size of the background noise or noise floor, so it is essential that a value for the smallest detectable anomaly is part of the survey specification. A survey completed with a large amount of instrument noise will still not detect smaller iron objects on the seabed even if a close runline spacing and low tow altitude is used. As shown in Figure 31 above, in shallow water where the towfish is on the surface and affected by movement by waves the noise floor can be 4nT to 8nT in size, giving a smallest detectable anomaly as big as 12 to 24nT. So the depth of water over the site and the weather at the time the survey is undertaken may have a significant effect on the smallest anomaly that can be detected.

In practice, an achievable magnetometer survey specification for underwater cultural heritage work is:

Runline spacing	15m
Towfish height	6m
Noise floor	2nT
So, minimum anomaly	5nT

Giving a minimum detectable target (MDT) size of: 500kg

The Problem with Poor Survey Specifications

The concept of a minimum detectable target (MDT) is not well known by underwater heritage practitioners. In the process of writing a theoretical study in to the use of marine magnetometers (Camidge et al 2010) we looked at a number of survey datasets and found that in many cases the actual depth of the towfish was not recorded so the altitude of the towfish could not be calculated. Runline spacing was often very large with the result that only iron or steel hulled vessels could have been detected and any remains of older vessels were missed. Many datasets were also very noisy so the noise floor was large meaning only the largest anomalies could be identified. So although a magnetometer survey had been completed, the size of the smallest target that could be detected during that survey could not be calculated.

It is reasonable generalisation that older shipwrecks will contain less iron and older ships are often of more interest as we know less about them. Yet, many geophysical surveys for heritage work have employed wide runline spacing, uncertain towfish altitude or noisy data which means that the most significant cultural material is not detected. For commissioned work where the commissioning organisation has accepted very poor quality data it suggests that the MDT was not a considered in the survey plan.

The solution to this problem seems to be the provision of proper specifications for marine magnetic surveys for underwater cultural heritage work followed by calculation of the achieved MDT for each part of the survey area as part of the post-processing phase.

Cables and Pipes

Cables and pipes are considerably longer than they are wide and produce effects on the Earth’s magnetic field which are larger than would be expected from the small mass of steel they are made from. Figure 32A shows the effect of a magnetometer run over a collection of power cables with steel armour on the outside; the large but narrow anomaly peaks are typical for this kind of target. The cables are close together so their magnetic effects overlap which makes it difficult to count how many there are in that area. One survey within Plymouth Sound detected a particularly unusual cable that produced a huge magnetic anomaly of nearly 15000nT (Fig. 32B right).

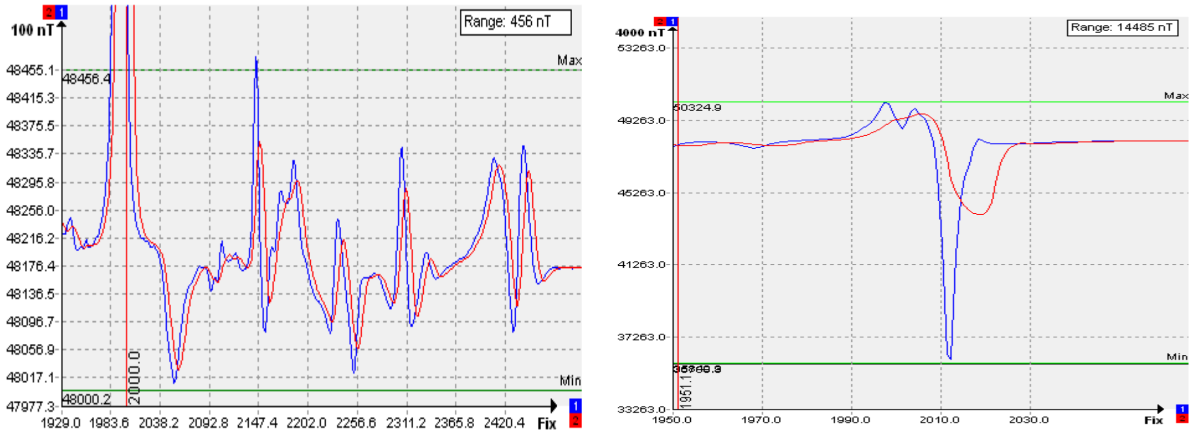


Figure 32A-B: A series of cables giving large magnetic anomalies (left) and a particularly large 14485 nT anomaly (right)

8. Reporting and Archiving

Introduction

Once the data has been processed the results can be collated into a report. The report can be used to document the results of the survey but it can also be used to record the methods used for data collection, processing and interpretation which will be of use to anyone wishing to reuse the data or to repeat the survey using different methods.

As a minimum, the report must contain a list of targets with estimates of position and depths as often the next step is to investigate each target using divers or an ROV. Another product of the survey could be a contour plot of the magnetic field in the survey area or a representation of the same field as a computer generated 3D surface. A complete report will contain detailed information about each target, a picture of the anomaly waveform, information about how the data was processed and how the data was collected. Results from marine geophysical surveys for archaeology are often reassessed at a later date when more work is to be done on a site so providing as much information as possible is useful.

Target List

As a minimum a report on paper must be provided containing a list of targets with estimated depth and position. You should also provide the same list in electronic form in a common file format such as Comma Separated Variable or CSV so the data can be easily imported into a GIS.

The names used for the targets in the report should be unique to that report as they are likely to be merged in a GIS with other, similar targets detected on other surveys and we need to be able to tell one target from another. So a target simply referred to as ‘T1’ in processing should have its name extended to uniquely identify it in any published reports or files. It is common to include a code name for the site and the year in a target name, for sites where more than one survey has been done in a year an additional survey number can be included. So target ‘T1’ on a survey in 2013 on the *Coronation* wreck in Plymouth could become ‘T13PLYCOR_1’ in the report.

How the positions of the targets are written in the report depends on the client’s requirements or the target audience. If there are no specifications for the survey then the most commonly used formats should be used.

- The estimated positions for the targets should be given as a latitude and longitude as this avoids any possible uncertainty in converting these positions to grid. The most commonly used format for a geographic position is degrees, minutes and decimal (DD MM.mmmm) in the form ‘50° 20.1234 N’. The geodetic datum must also be specified, usually WGS84.

- A precision of at least three decimal places must be given with four being the most usual for this kind of work as four decimal places gives a precision of ~0.2m. The geographic datum used for the positions should be included in the report, most often it is the WGS84 datum used by GPS receivers, and if the positions are given in grid co-ordinates the projection must also be stated.

- The target list should also include the size of the anomaly in nT relating to the target, or the largest anomaly if the target is detected on more than one survey line.

- If depth estimates are given for each target then they should be corrected for the effects of tide.

- The altitude of the towfish can be included, or an estimate calculated from towfish depth and water depth.

- The estimated mass of each target can also be included with a minimum and maximum mass given if a depth estimation has been calculated.

- A description of the target and anomaly can be useful, noting if the target was repeatable (detected on more than one line), clean or noisy, monopole or bipole in shape.

- For each target an image showing the associated anomaly is useful when re-interpreting the data.

```
Name    Tons Latitude      Longitude       Dep. Prio.  Description

T10_01  23T  50° 24.0051 N005° 53.6197 W  13m  High   23nT Clean, repeatable
T10_02  11T  50° 23.9032 N005° 53.6813 W  10m  High   12nT Noisy
T10_03  14T  50° 23.8574 N005° 53.6544 W  10m  High   13nT Clean
T10_05  32T  50° 24.0972 N005° 53.4542 W  15m  High   34nT Large, wide target
T10_11  16T  50° 24.1157 N005° 53.4716 W  15m  High   14nT Many small targets

T10_04  6T   50° 24.0684 N005° 53.6653 W  12m  Low    7nT Small
T10_06  3T   50° 24.0462 N005° 53.5853 W  13m  Low    4nT Small, in noise

All positions given in WGS84, depths to LAT in metres (estimated)
```

Figure 33: Example target list

Metadata

A report should also include information about the survey, the data and the processing; this is known as metadata. The metadata should include:

Magnetometer type	Specify the make and model, This is useful when reinterpreting the anomalies
Sample rate used	In Hz
Layback distance	Note the layback in metres, do this for each line if it is changed frequently
Positioning instrument	Specify the make and model as well as any differential corrections used so the precision (accuracy) can be estimated
Geodetic datum and projection	Give the name and parameters for the geodetic datum and map projection used for the survey data collection and processing.
Vessel offsets in metres	List these as offset in the forward and starboard directions
Heading instrument	If used
Boat speed	In knots or ms^{-1}
Average towfish depth	In metres
Average towfish altitude	In metres
Sea state	The sea state may affect the amount of swell noise
Estimate of the noise floor	In nT
Minimum detectable target	This is a useful metric for defining the quality of the survey
Processing software	Note the software type and version number so the archived data files can be read at a later date

Charts

As well as a list of targets it is usual to provide charts showing target locations so any patterns in the target distribution can be seen. The most basic chart would show just the targets in relation to one another but far more can be gained by including all of the relevant information used when processing using a GIS as described above.

Coverage Plot

A coverage plot is a chart showing the areas covered by the survey. For a survey done with uniform coverage with no problems this can be a simple chart with the area that has been surveyed shown as a filled shape. Sometimes it is not possible to cover the entire survey area because of obstructions, equipment failure or lack of time so publishing a detailed chart showing where data has been collected is essential. A refinement would be to show the track of the vessel superimposed over the filled shape on the chart. If the survey was completed with different line spacing in different areas then those areas need to be defined on the coverage plot because only larger targets can be detected in the areas with wider line spacing.

Minimum Detectable Target Plot

The most useful chart shows the minimum detectable target (MDT) value for each part of the survey area calculated from the noise floor, runline spacing and towfish altitude. This clearly identifies the areas where more work needs to be done to detect all the targets in the survey area that are above the minimum mass of iron given in the survey specification. This chart can be created by dividing up the survey area into small squares, calculating values for the noise floor and water depth, computing an MDT value for each square, then colouring each square on the chart according to the calculated MDT value.

Contour Plots and Surfaces

The results of marine magnetometer surveys can be presented as a contour plot, coloured surface or 3D surface model; these are representations of the same 3D model of the magnetic field over the site. For some sites this allows the survey results to be more easily understood and can be an aid to interpretation. Contour plots work very well when the size of the magnetic anomaly is much larger than the line spacing, such as the anomaly created by a large iron wreck (Fig. 34).

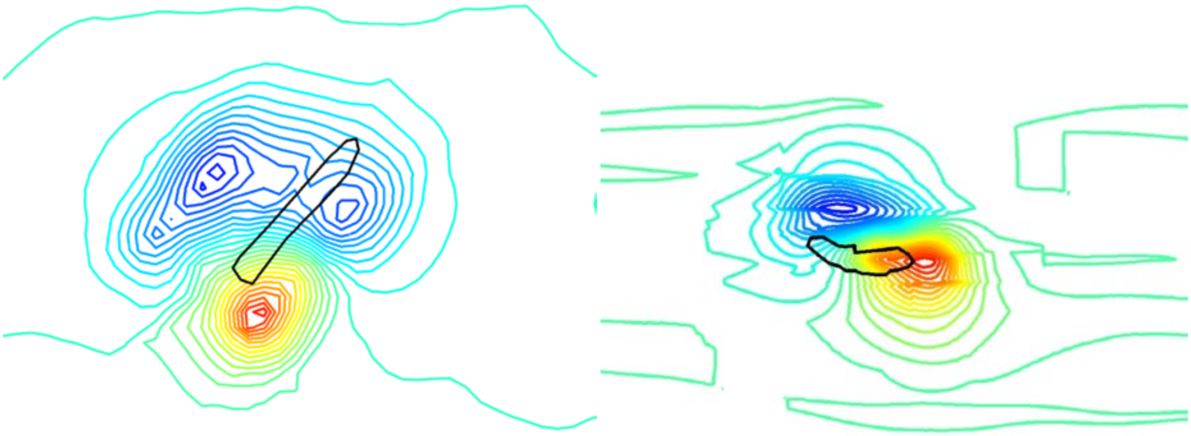


Figure 34: Magnetic field contour plots for the WWII Liberty ship SS *James Eagan Layne* (left) and the WWI steam collier SS *Rosehill* (right)

Unfortunately, for survey areas containing small scattered targets the resulting contour plot is often a misrepresentation and in some cases it can hide important details. The plot can give a false impression of the site and its targets unless the data has been specifically collected and processed with this type of product in mind.

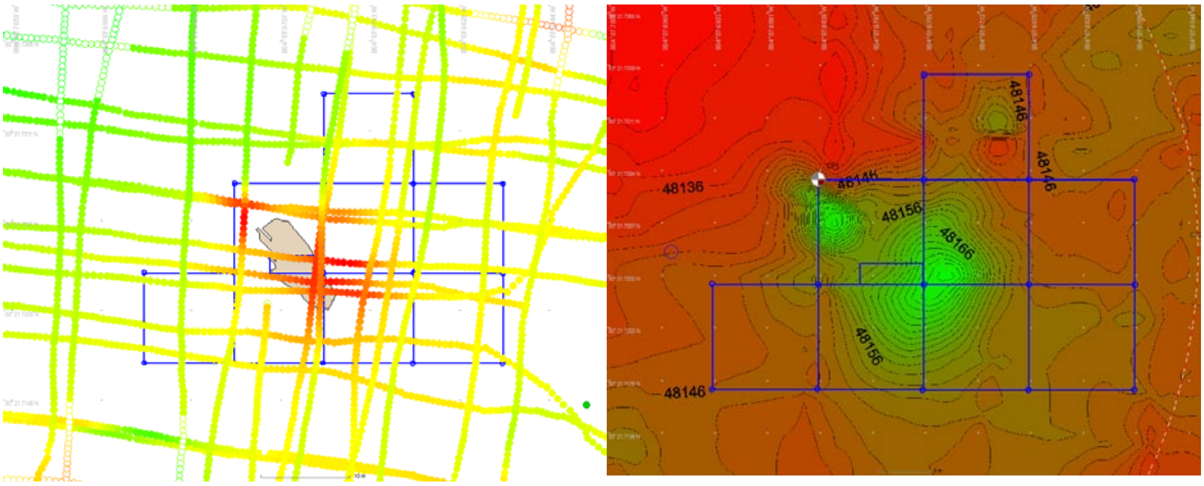


Figure 35: Detailed coverage with even line spacing and the resulting contour plot (grid square 10m)

If a contour plot or surface is required as a product then it is essential that an even coverage is completed at a high resolution. Problems occur where too wide a line spacing is used. For example, the sample interval in metres along the track of the vessel may be 0.2m if a high sample rate magnetometer is used but the sample interval across the track is the same as the line spacing and may be 15m or more. So the data we use to create the contour plot can be very detailed in one direction and have little or no detail in another, which causes problems when we try and create a contour plot.

The problem can be solved in part by running cross lines at 90 degrees to the survey lines at the same line spacing (Fig. 35). This produces a grid of measurements which tells us much more about the magnetic field between the survey lines. The drawback is that it takes twice as long to collect the data.

For single small targets their anomaly field can be mapped by running across the target in a star pattern with the target in the centre (Fig. 36A). This produces a dataset with a high density of measurements concentrated on the target itself but with additional less dense information further away. This is appropriate for magnetic anomalies as they change shape the most when close to the target.

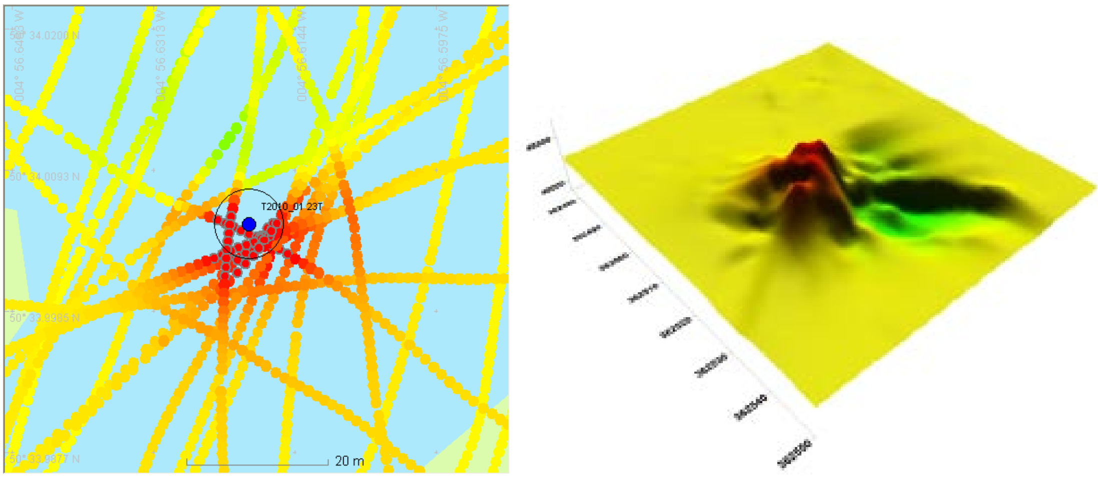


Figure 36A and B: Star pattern coverage and equivalent 3D representation

The method used for converting the field measurements to a grid also affects the resulting contour plot. The point measurements are converted to a regular grid using a mathematical technique and there are many different ways to do this, but the most commonly used software is Surfer by Golden

Software. The regular grid can then be used to create contour lines of equal field strength or be converted into a 3D surface (Fig. 37). Problems can occur in the conversion because of the shape of magnetic anomalies and the assumptions of the gridding and contouring process.

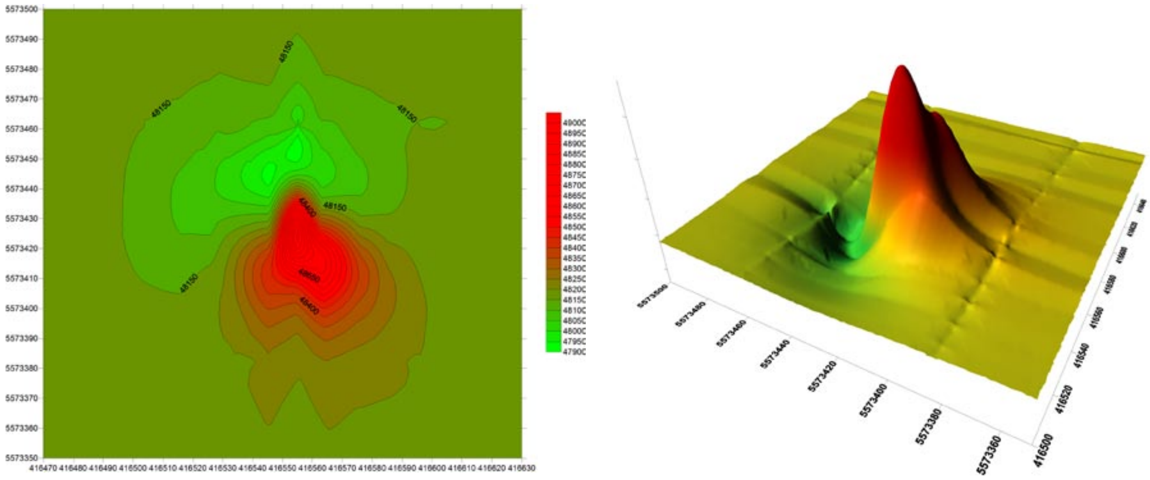


Figure 37A and B: Contour plot and equivalent 3D representation

A good example of the problem can occur when there are two small anomalies on adjacent survey lines. Anomalies from small targets are often nearly circular in shape so are as wide as they are long in size. An anomaly that is smaller in length than the line spacing will only be detected on one survey line, but as there is no additional information about the anomalies between the two adjacent survey lines the contouring process may assume that they are actually the same anomaly and will join contours between them. This makes two small anomalies into one very much longer one with the same length as the line spacing, making the anomalies look far larger than they are.

Another problem is the effect of uncorrected and unfiltered data. Creating contour plots from data that has not been levelled or corrected for diurnal variation produces 3D surfaces that are lumpy and uneven in long lines across the survey area (Fig. 38). Using data that contains wave noise produces colour plots with ‘tiger stripes’ along the lines. Neither plot would be an accurate representation of the magnetic field over the site and are of little practical use.

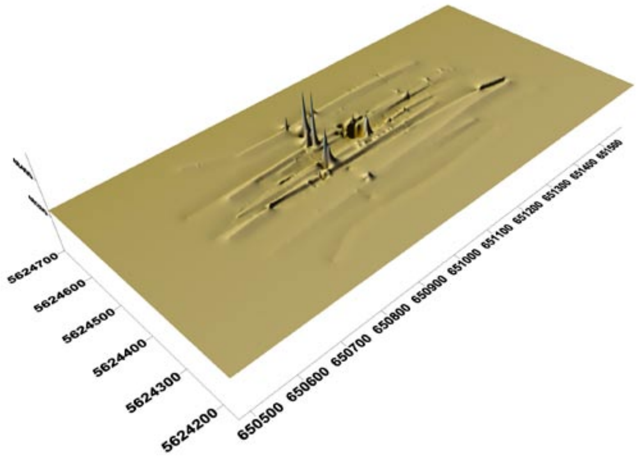


Figure 38: Poorly processed magnetometer data (Anon.)

The contour plots and 3D models can also give a false impression of the site in areas cluttered with modern iron debris or cables. The modern debris and cables can produce very large magnetic anomalies which may be many times larger than the anomalies produced by the wreck debris we are interested in. A contour plot or 3D surface scaled to show the larger clutter targets may suppress the smaller, wanted targets so they can no longer be seen. Figure 35 shows a 3D plot that includes large modern debris but the scale used for the plot effectively hides the more interesting older targets as they are small.

Archiving

A basic survey report should contain enough information to describe each target sufficiently for each to be investigated but a more detailed report would help others repeating the survey work at a later date. The ideal would be to allow others to reprocess the data collected on your survey as better methods for processing may be available in the future. This means that the information from your survey should be stored in an archive.

The archive should contain enough information for others to repeat the same data processing tasks.

This requires the archive to have a complete set of data in file formats that can be read at a later date. It is essential to include the raw data in the archive in a non-proprietary and very common format so it has the highest chance of being read and understood many years later when file formats and standards may have changed.

- Metadata in CSV (Comma Separated Variable) or text format
- Raw data in CSV format
- Target list in CSV format
- Report in raw text format
- Report as published in common format (MS Word, HTML, RTF)
- Processed files in processing application native format
- Target images in common lossless file format (TIF, PNG), do not use lossy format like JPG.

9. Bibliography

Aspinall A., Gaffney C. & Schmidt A., 2008, *Magnetometry for Archaeologists*, AltaMira Press, ISBN 0 7591 1106 5

British Geological Survey, The Earth's Magnetic Field: An Overview, Available at: http://www.geomag.bgs.ac.uk/education/earthmag.html

Camidge, K., Holt, P., Johns, C., Randall, L., Schmidt, A. (2010) Developing Magnetometer Techniques to Better Identify Submerged Archaeological Sites – Theoretical Study Report (5671 DT), Cornwall Council, Truro, Available at: www.cismas.org.uk/downloads

Hall E. T., 1966, The Use of the Proton Magnetometer in Underwater Archaeology, Archaeometry Volume 9, Issue 1, pages 32–43

Holt, P., 2010. *Geophysical Investigations of the Cattewater Wreck 1997-2007,* Available at: www.3hconsulting.com/SitesCattewater.htm

Hrvoic, D, 2014, High-resolution near-shore geophysical survey using an Autonomous Underwater Vehicle (AUV) with integrated magnetometer and side-scan sonar, *Open Access Dissertations and Theses.* Paper 8955.
http://digitalcommons.mcmaster.ca/opendissertations/8955

Plets, R., Dix, J., Bates, R. (2013) *Marine Geophysics Data Acquisition, Processing and Interpretation – Guidance Notes*, Available at: http://www.english-heritage.org.uk/publications/marine-geophysics-data-acquisition-processing-interpretation

Kearey P., Brooks M., Hill I., 2002, *An Introduction to Geophysical Exploration*, 3rd Ed., Blackwell Publishing, ISBN 978 0 632 04929 5

Milsom J., 2003, *Field Geophysics*, 3rd Ed., John Wiley & Sons Ltd., ISBN 0 470 84347 0

All online documents were available at the time of publication.

Note:
The pictures of time series plots and charts were created using the Site Searcher magnetometer data collection and processing software from 3H Consulting Ltd.

Marine Magnetometer Processing

3H Consulting Ltd.
www.3HConsulting.com

3H
Consulting