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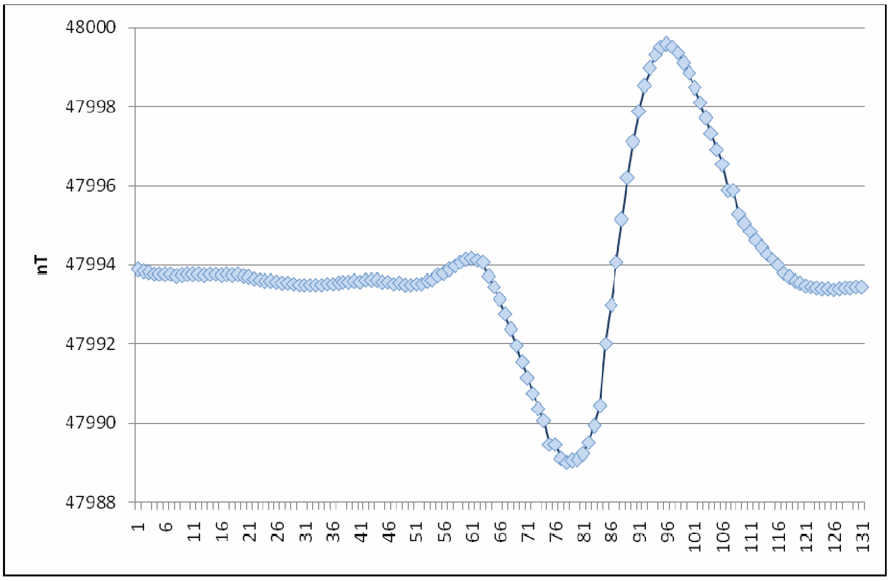
Developing Magnetometer Techniques to Identify Submerged Archaeological Sites

Theoretical Study Report



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CORNWALL COUNCIL

Historic Environment Projects

Developing Magnetometer Techniques to Identify Submerged Archaeological Sites

Theoretical Study Report

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Within Historic Environment, the Project Manager was Charles Johns.

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Cover illustration

Dipole mag series graph (Kevin Camidge)

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Abbreviations

AAF	Archaeological Archives Forum
ALSF	Aggregates Levy Sustainability Fund
ASW	Anti-submarine warfare
AUV	Autonomous Underwater Vehicle: an untethered underwater robot
BMAPA	British Marine Aggregates Producers Association
CISMAS	Cornwall and Isles of Scilly Maritime Archaeology Society
EGNOS	European Geostationary Navigation Overlay System
EH	English Heritage
GPS	Global Positioning System; a surface positioning system that uses satellites
HER	Cornwall and the Isles of Scilly Historic Environment Record
HE Projects	Historic Environment Projects, Cornwall Council (formerly HES)
HES	Historic Environment Service (Projects), Cornwall County Council
HWTMA	Hampshire and Wight Trust for Maritime Archaeology
ICH	Integrated Coastal Hydrography
LBL	Long BaseLine: a sea-referenced underwater acoustic positioning system
MEDIN	Marine Environmental Data & Information Network
NGR	National Grid Reference
NMR	National Monument Record, Swindon
OASIS	Online Access to the Index of Archaeological Investigations
OS	Ordnance Survey
ROV	Remotely Operated Vehicle: an untethered underwater robot
RTK GPS	Real Time Kinematic GPS: a high accuracy surface positioning system
SNR	Signal to Noise Ratio
UKHO	United Kingdom Hydrographic Office, Taunton
UPD	Updated Project Design
USBL	Ultra Short BaseLine. A vessel based underwater acoustic positioning system
UXO	Unexploded Ordnance
VENUS	Virtual ExploratioN of Underwater Sites
WA	Wessex Archaeology Ltd
WAAS	Wide Area Augmentation System

Definition of Terms

Along track	In the direction in which the Towfish is being towed
Anomaly	The variation in the magnetic field caused by a magnetic target
Altitude	The towfish altitude is the distance of the towfish above the seabed
Crossline	A survey line run at 90° to the main Runline direction
Cross track	A direction at 90° to the heading in which the Towfish is being towed
Depressor	A wing attached to a Towfish to make it tow deeper in the water
Diurnal	Diurnal variation is the daily variation in the earth's magnetic field
Filtering	Removal of unwanted information from a dataset
Heading error	Error in the magnetic field measurement related to the heading of the sensor
Layback	The distance the magnetometer towfish is towed behind the boat
MMS	Mineral Management Service, USA
nano Tesla (nT)	A unit of magnetic field strength
Noise	The unwanted component of measurements made by the magnetometer
Range	The range to target is the horizontal distance between the magnetometer towfish and the target
Regional	Regional variation is variation in the magnetic field strength caused by geological features
Runline	A survey line along which the towing vessel is steered
Sample rate	The rate at which magnetic field measurements are made, measured in Hertz (Hz)
Sensitivity	A measure of the smallest magnetic field variation that a Magnetometer Sensor can detect
Signal to Noise Ratio	The ratio of the wanted signal level to the Noise level measured by the magnetometer Sensor
Slant Range	The slant range to the target is the direct distance between the magnetometer towfish and the target
Spike	A component of Noise with a short duration but a high level
Swell noise	Noise in the measurements caused by the motion of sea water waves in the Earth's magnetic field
Target	The object causing the magnetic anomaly
Timeseries plot	The magnetic field strength plotted against time or distance
Tow cable	The cable that connects the magnetometer Towfish to the towing vessel
Towfish	The magnetometer towfish contains the magnetometer sensor(s)

1 Summary

In March 2009 English Heritage commissioned Historic Environment Projects, Cornwall Council to carry out an initial theoretical study to result in an Updated Project Design (UPD) to inform field trials of different types of marine magnetometer in controlled conditions. The project was funded through the Aggregates Levy Sustainability Fund (ALSF). The main part of the theoretical study was carried out by a team of external maritime and/or geophysics specialists.

Marine magnetic surveying has become a standard technique for mapping the location of ferrous material on the seabed. Existing guidance documents are concerned principally with data collection methods. The aim of the project was to acquire a better understanding of magnetic data and thus develop our ability to interpret these data with increased confidence.

It was envisaged that the main product of the completed project would be a viable methodology and guidance for general use of magnetometers in marine historic environment investigations and for the interpretation of the acquired data. This would contribute to the better management of known wreck sites in marine aggregates producing areas, help to inform license applications for marine aggregate dredging, enhance the ability to assess archaeological potential and has potential benefits in reducing the time and cost of marine investigations.

The scope of the theoretical study included existing literature, and guidance on the use of magnetometers in marine archaeological surveys, performance, targets and signals, deployment, post-acquisition processing of data, archiving, and publication. The results are presented in this report; the study calls into question Hall's equation upon which interpretation of magnetic data has been based since 1966 and recommendations are made for conducting magnetic surveys and for further investigation.

Following submission of the draft theoretical report English Heritage decided not to move forward with the UPD and fieldwork stage partly in view of the current guidance on marine geophysics being prepared by Dr Justin Dix of Southampton University and partly because of an advised cut to next year's ALSF budget. The recommendations resulting from this study will therefore be incorporated into Dr Dix's forthcoming guidelines.

2 Introduction

2.1 Project background

In March 2009 Historic Environment Projects, Cornwall Council (HE Projects) was commissioned by English Heritage through the Aggregates Levy Sustainability Fund (ALSF) to carry out an initial theoretical study resulting in an Updated Project Design (UPD) to inform field trials of different types of marine magnetometer in controlled conditions. The main part of the theoretical study was carried out by the project team of external maritime and/or geophysics specialists.

Following submission of the draft theoretical report English Heritage decided not to move forward with the UPD and fieldwork stage partly in view of the current guidance on marine geophysics being prepared by Dr Justin Dix of Southampton University (Dix *et al* 2008) and partly because of an advised cut to next year's ALSF budget. The recommendations from this study will therefore be incorporated into Dr Dix's guidelines.

Different types of marine magnetometers are often used in conducting archaeological surveys of the seabed for Environmental Impact Assessments and other studies in order to detect metallic objects on or buried below the seabed. Interpreting magnetometer data from a number of development-led seabed surveys (eg HMS Scylla for Plymouth National Marine Aquarium, the South West Wave Hub for Halcrow, the Falmouth Cruise project for Haskoning UK Ltd) had convinced us that a better understanding of these data, and thereby improved recognition of archaeological remains on the seabed, could be reached by conducting trials of different marine magnetometers in controlled conditions.

2.2 Application of magnetometer surveys to marine aggregates areas

Magnetometer surveys are usually used in conjunction with other marine geophysical survey techniques; the data being correlated in particular with side scan sonar survey. The main use is for the detection and/or survey of wreck sites and scattered wreck debris (cf Dix *et al* 2008). Such surveys can enhance existing information about known wreck sites and contribute to the better management of known wreck sites in marine aggregates producing areas.

A better understanding of magnetic data, and thereby improved recognition of archaeological remains on the seabed, will inform license applications for marine aggregate dredging, enhance the ability to assess archaeological potential and have potential benefits in reducing the time and cost of marine investigations.

It will also assist seabed developers, their archaeological advisors and heritage curators in assessing maritime archaeological potential on the seabed during the preparation of dredging work proposals.

2.3 Aims

The aim of the theoretical study was to enable a better understanding of marine magnetic data, leading to enhanced interpretation of magnetic survey data.

The main objectives of this stage of the project were as follows:

- to undertake a theoretical study of literature relating to the use of magnetometry in surveys of the marine historic environment;
- to report on the results of the theoretical study; and
- to highlight areas where practical trials are needed to resolve issues.

2.4 Methods

The methodology for the theoretical study was outlined in the project design (Camidge *et al* 2009). The theoretical study addressed the following themes: existing literature and guidance on the use of magnetometers in marine archaeological surveys, performance, targets and signals, deployment, post-acquisition processing of data, archiving and publication.

A summary of the main literature consulted appears in the Appendix at the end of the report.

3 Results of the theoretical study

3.1 Introduction

3.1.1 Marine magnetometers

A magnetometer is an instrument which measures the intensity of a magnetic field. Their application in geophysical prospection is founded on the principle that they can measure and record deviations in the Earth's ambient magnetic field brought about by the presence of ferromagnetic material. Although the concept of identifying deviations within the Earth's magnetic field has been used in mineral prospection since the 17th Century, when a compass was used to identify the presence of buried iron ore, the earliest practical magnetometer was not developed until 1832 (Aspinall *et al* 2008, 2). Early magnetometers, also referred to as variometers, consisted of a suspended permanent bar magnet.

The requirement for rugged and portable magnetometers for use in Anti-Submarine Warfare (ASW) during World War Two lead to significant developments in magnetometer sensor technology, particularly that of the fluxgate magnetometer (Kearey *et al* 2002, 162). During the latter half of the 20th Century proton-precession magnetometers were employed in maritime archaeological surveys (Arnold 1981; Arnold and Clausen 1975; Hall 1966). A development of the proton-precession magnetometer sensor made during the 1970s was the Overhauser magnetometer, which is capable of near continuous output and high sensitivity (Hrvoic *et al* 2003 in Aspinall *et al* 2008, 47). A further development in magnetometer sensor technology was the caesium vapour magnetometer, which has improved detection levels compared to either fluxgate or proton instruments (Aspinall *et al* 2008, 52.) Although marine proton-precession magnetometers are still commercially available, current guidelines (Dix *et al* 2008, Wessex Archaeology 2007, MMS 2004) recommend the use of Overhauser or caesium-vapour magnetometers for marine archaeological surveys.

Parallels can be drawn between maritime archaeological prospection and other applications of magnetometer surveys, such as terrestrial archaeological prospection, marine geological surveys and Unexploded Ordnance (UXO) detection. Magnetometer surveys on land have more accurate positioning of the instrument as well as smaller distance between the magnetometer and features under investigation. Fluxgate magnetometers are common in terrestrial surveys, where gradiometers (ie more than one sensor, see Section 3.4.5) are typically employed. As vector magnetometers, such as fluxgates, measure a component of the magnetic field in a particular direction (Aspinall *et al* 2008, 29) they are rarely used in marine surveys where variations in attitude and yaw of the towfish are likely. For this reason scalar magnetometers (ie proton, Overhauser and caesium vapour) which measure the strength of an ambient magnetic field at any given point (Aspinall *et al* 2008, 29) are used in marine surveys.

The application of marine magnetometer surveys in UXO detection is in many ways the most similar to marine archaeological survey. The targets of both surveys are of comparable mass, both experience significant separation of the magnetometer from the targets under investigation and the same difficulties in fixing the position of the towfish. The requirement for high resolution data in UXO detection has driven the development of analytical signal gradiometers (Hrvoic and Pozza 2004) and developments made in the field of marine UXO detection are likely to be of relevance to magnetometer surveys in maritime archaeological prospection

3.2 Guidance notes

Several documents exist which are intended as guidance notes for marine geophysical survey, with sections pertaining to magnetometer surveys. A number of additional sources have been consulted, which while not intended as guidance notes nevertheless offer specific recommendations for magnetometer surveys.

Author	Date	Title
Dix *et al*	2008	*Marine Geophysical Instrumentation Acquisition, Processing and Interpretation* (draft report) ALSF
Hall	1966	The use of the proton magnetometer in underwater archaeology. *Archaeometry* 9(1)
MMS (Minerals Management Service, USA)	2004	*Archaeological damage from offshore dredging: recommendations for pre-operational surveys and mitigation during dredging to avoid adverse impacts*
Wessex Archaeology	2003	Marine aggregate dredging and the historic environment – assessing, evaluating, mitigating and monitoring the archaeological effects of marine aggregate dredging: guidance note (BMAPA and EH)
Wessex Archaeology	2004	Guidance note on assessing, evaluating and recording wreck sites (draft report)
Wessex Archaeology	2006(a)	Wrecks on the Seabed Round 2: assessment, evaluation and recording - geophysical survey report
Wessex Archaeology	2006 (b)	Salcombe Cannon Site, Devon: designated site assessment report
Wessex Archaeology	2007	Historical environment guidance for the offshore renewable energy sector (COWRIE)
Wessex Archaeology	2008	Air crash sites at sea, a scoping study: archaeological desk-based study

Fig 1 Summary of guidance notes

3.2.1 Magnetometer towfish altitude (height above seabed)

The clearest statement is made by (Dix *et al* 2008) where a towfish altitude of 6m or less is recommended. Wessex Archaeology (WA) make a number of statements concerning towfish altitude, 'The magnetometer is typically towed near to the seabed…' (WA 2004). The guidance note (WA 2006a) used two different towfish depths 'shallow' and 'deep' but the actual depths are not specified. Hall (1966) does not give any specific depths, but does give some detail on how to control towfish depth. Most papers advise that the towfish altitude must be determined by the minimum iron mass to be detected, this is probably the best approach. For discussion of magnetometer towfish altitude see Section 3.6.1 below.

3.2.2 Runline spacing

A runline spacing of 30m x 30m (line spacing of 30m with cross lines every 30m) is recommended (Dix *et al* 2008) for large area surveys and 10m x 10m for detailed surveys. A spacing equal to the maximum detectable distance is recommended by Hall (1966).

The Minerals Management Service USA (MMS 2004) records a number of recommended line spacings used in various regions of the USA where 30m line spacing is common; Florida recommends 30m above the 100ft contour and 50m below the 100ft contour. North Carolina suggests 18m while Jacksonville prefers 23m. The Institute for International Maritime Research has adopted 15m line spacing to identify 'early wrecks'. Wessex Archaeology (2004; 2006a) recommend run line spacing of 25m or less and cross lines at 5x the line spacing.

Having analysed magnetometer data for a range of shipwrecks, Enright *et al* (2006) conclude that all of the wreck sites studied would have been detected by at least one run line at 40m line spacing (p 129) and at least two run lines at 20m line spacing (p 133). It is important to note that the study by Enright *et al* (2006) only deals with shipwrecks and not items of debris.

See below, run line spacing Section 3.8.1 and towfish altitude Section 3.6.1.

3.2.3 Layback

Dix *et al* (2008) state that the magnetometer layback should be equal to twice the survey vessel length. Wessex state that the magnetometer should be towed sufficiently behind the survey vessel to avoid detection of the survey vessel (WA 2004). Hall (1966) advises a tow cable length of 2.5 times the length of survey vessel for iron hulls, and of about 30m for vessels with wood or GRP hulls.

See below, layback Section 3.7.3

3.2.4 Magnetometer type

Caesium vapour magnetometers are recommended by Dix *et al* (2008). Wessex Archaeology suggest 'optically pumped or equivalent' devices (caesium vapour magnetometers are of the optically pumped type). 'Today state-of-the-art magnetometers use caesium vapour or hydrogen... for high sensitivity and low noise' (MMS 2004).

See below, magnetometer types Section 3.4.1

3.2.5 Position fixing

Position fixing is achieved by use of GPS. Differential GPS (DGPS) is recommended by Dix *et al* (2008). The problems and expense of using RTK GPS systems are discussed in Wessex Archaeology (2004) while in Wessex Archaeology (2003) positioning to 1m or better is recommended.

See below, positioning Section 3.7

3.2.6 Smallest detectable anomaly

Dix *et al* (2008) state 'In practice the smallest change in the magnetic field that can be reliably detected is 5 nT'. This is confirmed by Wessex Archaeology where targets of less than 5 nT are deemed unlikely to be of archaeological significance (WA 2006a) and 'amplitudes of less than 5 nT were not recorded' (WA 2008). Interestingly in the former report (WA 2006a) targets of less than 3 nT total deflection were selected in the target list (WA 2006a, Appendix X).

In practice a minimum detectable deflection of 5 nT may be a little on the conservative side; where the data are relatively noise free 3 or even 2 nT may be practical. In practice targets smaller than 5 nT deflection are sometimes selected. This will depend on the noise levels encountered in the data and may well be affected by instrument type and data rate (see section 3.4.3). The smallest detectable anomaly needs to be established under controlled conditions for the principal types of magnetometer (data rate may influence effective minimum detectable anomaly – see 3.4.3).

3.2.7 Tow speed and sample rate

Dix *et al* (2008) state that 'At no point should the speed exceed 4 knots. Ideally, the speed over the ground should be limited to 2.5 knots to 3 knots'. While Hall (1966) states that there are three factors to be considered in determining tow speed, fish depth, anomaly size and polarisation/data rate – he states that 5 knots is usually satisfactory. None of the other papers studied gave any recommendations concerning desirable data rate or tow speed.

Data rate and tow speed need to be considered together along with the minimum target mass to be detected to arrive at a suitable combination of data rate and tow speed – smaller targets will require higher data rate to detect the signal within the noise and/or a lower tow speed. The minimum tow speed will be determined by wind and sea conditions as well as vessel characteristics – there will be a minimum speed at which accurate steerage can be maintained by the survey vessel.

3.2.8 Survey data format

Dix *et al* (2008) recommend that final output should be an ASCII text file containing location, depth and *adjusted* magnetic value (x,y,z value). Wessex Archaeology state that data should be smoothed, corrected for layback and maintained as an xyz file (2004, 27); also that magnetic data should be made available as cleaned, de-spiked text (x,y,z) files for each run line, including layback (WA 2007).

3.3 Survey Reports

3.3.1 Introduction

In order to indicate present magnetometer survey and reporting practices relevant to aggregate extraction areas, attempts were made to source relevant archaeological survey reports from this sector. To this end English Heritage, BMAPA, the Crown Estate, the Marine and Fisheries Agency, EMU, Fugro Ltd, Henson Aggregates Marine Ltd and Wessex Archaeology were contacted. In general surveys are done directly for aggregate companies by commercial survey companies, who hold the raw data. The data is interpreted by an archaeological organisation but the interpreted survey reports are difficult to obtain because of issues of client confidentiality, and unfortunately, only a single survey report including details of a marine magnetometer survey was found to be available. We are grateful to Wessex Archaeology Ltd and Volker Dredging Ltd for making this report available and to the aforementioned organisations for their assistance in our enquiries.

To supplement this single report, a further nine archaeological survey reports not relating to aggregate extraction areas have been included in this literature review. Five of these reports relate to targeted surveys of known archaeological sites (including two areas designated under the Protection of Wrecks Act 1973) and aim to quantify the nature and extent of existing cultural material. The remaining four reports are archaeological appraisals and as such were designed to identify hitherto unrecognized sites of archaeological potential.

These ten reports are individually summarised below and comparisons drawn in Figure 2.

3.3.2 Area surveys

Median Deep: Area 461 Archaeological Assessment of Geophysical Data

(Wessex Archaeology 2006c)

This is a report detailing the collection and interpretation of geophysical data as part of the archaeological evaluation of a proposed aggregate dredging area located approximately 50 km off Beachy Head, in the English Channel. The geophysical survey undertook to collect magnetometer data, side scan sonar records, sub-bottom profile data and multi-beam swath bathymetry. Vibra-core samples were also collected and a drop-down video platform was employed in the investigation of selected anomalies.

The survey covered an area of approximately 6 km^2 in water depths of 35 – 45m below chart datum. Magnetometer, side scan sonar, sub-bottom profile and multi-beam data were collected concurrently, using E-W runlines spaced at 115m. Four cross-lines were also collected, oriented N-S, the spacing of which is not stated. Differential GPS was employed for position fixing. Due to large layback distances a USBL system was employed to more accurately position the side scan sonar instrument but not the magnetometer. The magnetic survey was undertaken using a Marine Magnetics SeaSpy Overhauser instrument. The layback distance for the magnetometer instrument is stated as 150m, and it is commented that without the use of a USBL system the associated positional data is of low resolution.

The magnetic data-set was post-processed to adjust for layback and remove regional & diurnal magnetic variations. It is stated that the resultant files contained positional data (UTM grid co-ordinates) and total field strength readings. No mention is made of the collection of instrument depth or altitude data, or of its use in the interpretation of the data-set. The magnetometer data was plotted and interpreted as a colour banded contour map, which is reproduced in the report. Two targets of Low Archaeological Potential, effecting deflections of 8nT and 12nT, are identified. Targets of Low Archaeological Potential are defined as:

'Small, isolated, geophysical anomalies of unclear origin' (pp 6)

Neither magnetic anomaly corresponded to a side scan sonar target and so were not investigated using the drop-down video platform.

HMS *Scylla* – Whitsand Bay, Cornwall: archaeological assessment

(Historic Environment Service, Cornwall County Council 2004)

An assessment of geophysical data collected for the area where HMS *Scylla* was to be sunk as an artificial reef (Johns *et al* 2004). Magnetometer data was collected using a proton-precession sensor in support of side-scan sonar, multi-beam and sub-bottom profile surveys.

Ten survey lines had been completed over the survey area at 50m line spacing. The resulting data was presented for interpretation as a printed (ie hard copy) timeseries plot printed to a scale of approximately 1:15,000. It is suggested that at this scale the minimum observable anomaly was 10nT, equivalent to targets of between four and ten tonnes depending upon water depth. No indication of instrument altitude/depth was provided with the magnetometer data. Surface tow is therefore assumed, in water of up to twenty-five meters in depth. Four anomalies of archaeological potential are identified.

It is made clear from the appraisal of the data that the survey methodology employed was not suitably designed for the detection of typical archaeological targets, which fall well below the minimum target mass detectable (*c* 4 – 10 tonnes). Both fish altitude and line spacing were insufficient.

South West Wave Hub - Hayle, Cornwall: archaeological assessment

(Historic Environment Service, Cornwall County Council 2006)

This was an assessment of geophysical data collected for the area intended for the installation of the South-west Wave Hub (Camidge *et al* 2006). Magnetometer data had been collected, along with side-scan sonar and sub-bottom profiles, using a Marine Magnetics SeaSpy Overhauser sensor. The data was provided for assessment as *x,y,z* ASCII files.

The marine magnetic survey had been conducted using 75m and 100m line spacing. The depth of water in the survey area ranged from 0-60m. No instrument altitude/depth data recorded in the data set but a maximum fish depth of 3m was asserted.

The data was interpreted as timeseries plots and the observed anomalies plotted in AutoCAD to show correlation between magnetometer and side-scan sonar targets. Forty anomalies of archaeological potential are identified from the data set. It is stated, however, that the minimum detectable target in the deep (60m) section of the survey area is between nine and forty tonnes. Again, it is made clear in the appraisal of the magnetometer data that neither suitable instrument altitude nor line spacing was employed in the survey. The minimum target detectable in the deeper areas of the survey (9 – 40 tonnes) equates to small vessels of steal construction rather than even significantly sized earlier vessels.

Falmouth Cruise Project: archaeological assessment

(Historic Environment Service, Cornwall County Council 2008)

This was an assessment of geophysical survey data collected in advance of proposed dredging activity in Falmouth docks (Johns *et al* 2008). Magnetometer data was collected in addition to side-scan sonar, sub-bottom profile and bathymetric data using a Geometrics G-882 Caesium vapour sensor. Two different sensors were used in the course of the survey, one employing a depth sensor and the other an altimeter.

The marine magnetic survey was completed using 10m line spacing and typical instrument altitude of 4-6 m. Bathymetric data was collected simultaneously to allow for improved accuracy of target mass estimation using the Hall equation. A Real Time Kinematic (RTK) GPS was used to accurately fix the survey vessel's location, this GPS was checked against a known location at the start and end of each day.

The resulting magnetic survey data was interpreted as timeseries plots and the observed anomalies plotted in AutoCAD to show correlations between magnetometer and side-scan sonar targets. It is reported that the survey was continually interrupted by small boat traffic and a table of anomalies known to have been caused by such traffic is presented.

Nine magnetic anomalies, all of which correspond with side-scan sonar targets, were investigated using a Remote Underwater Vehicle (ROV).

3.3.3 Targeted archaeological surveys

HMS *Colossus* Debris Field Survey

(CISMAS 2005)

This is a report on a marine magnetic survey of the protected wreck site of HMS Colossus in the Isles of Scilly (Camidge and Witheridge 2005) which complemented an earlier survey conducted by the Archaeological Diving Unit (ADU) utilising a similar survey methodology and equipment. Magnetometer data were collected using a Geometrics G-881 Caesium Vapour sensor and recorded in *Site Searcher* software from 3H Consulting Ltd. The report does not state the sample rate used.

The survey vessel was positioned using a Garmin EGNOS enabled GPS and bathymetric data were collected simultaneously to allow for improved accuracy of target mass estimation using the Hall equation. The survey was completed using 15m line spacing and a fish altitude of 7m to 16m. Layback corrections were automatically applied in *Site Searcher*.

The magnetometer data was interpreted as timeseries plots and any observed anomalies plotted in AutoCAD to facilitate the identification of correlated targets. Two hundred and ninety-one targets were identified and prioritised for investigation according to estimated mass. One-hundred and three of the magnetic anomalies were investigated and the results are summarised.

Marine Magnetic Survey of a Submerged Roman Harbour, Caesarea Maritima, Israel

(Boyce *et al* 2004)

This is a journal article detailing a pilot study intended to evaluate the application of marine magnetic survey in mapping submerged hydraulic concrete foundations. Prior to undertaking the magnetometer survey, core samples of hydraulic concrete, harbour sediments and local bedrock were analysed for magnetic susceptibility in order to indicate the expected contrast between these materials. This analysis demonstrates that the magnetic susceptibilities of hydraulic concrete are one to two orders of magnitude higher than that of harbour sediments. This is accounted for by the presence of magnetic oxides present in the volcanic ash and tuff which constitutes 20 - 40 % by volume of the hydraulic concrete under investigation.

The geophysical survey undertaken covered an area of 1km^2 using gridded runlines at intervals of 10 – 20m, in water depths of 4 – 10m. The magnetometer survey employed a Marine Magnetics SeaSpy Overhauser instrument fitted with a depth sensor and operating at a frequency of 4 Hz. Bathymetric data was collected simultaneously in order to later calculate instrument altitude. The geophysical survey data were positioned using differential GPS. A proton magnetometer base station was also employed on land to facilitate removal of diurnal variations (see Section 3.9.1.4) in post-processing.

Following extensive post-processing including layback correction, removal of diurnal variations and draping of data to account for variations in instrument-altitude (see Section 3.9.3.8), the presence of hydraulic concrete foundations is evidenced in the data by a series of magnetic anomalies ranging from 3 – 10 nT in size.

Study to Conduct National Register of Historic Places Evaluations of Submerged Sites on the Gulf of Mexico Outer Continental Shelf

(Enright *et al* 2006)

This is a report detailing the investigation of side scan sonar targets previously identified in the course of industry surveys preceding drilling or pipeline construction in the Gulf of Mexico. For each site geophysical assessment was undertaken, employing both side scan sonar and magnetometer survey. Visual inspection of any anomalies was then carried out using either an ROV or archaeological diver. The results of the geophysical and visual surveys are accompanied by conclusions drawn from documentary research and site specific mitigation practices are detailed. There is no mention made to the collection of bathymetric data or there use in the interpretation of the magnetic survey data. A total of fourteen sites, in water depths of 7 – 37m, were subject to investigation.

For each site a magnetometer survey was undertaken using a Marine Magnetics SeaSpy Overhauser instrument operated at 1 Hz. Runline spacing of 10m or less was employed for all magnetometer surveys, with instrument altitude reported between 5 – 22m depending on the site. Differential GPS was employed to facilitate sub-metric position fixing, with all positional data logged in UTM, and *HydroPro* software utilised to adjust for layback in real time and log all positional data. It is not mentioned whether raw (unadjusted for layback) data were also recorded.

It is stated that for three of the targets under investigation (Sites 409, 410 & 324) no anomalies were detected following geophysical survey. For two of these sites, 409 & 410, alternative positions are postulated distanced 6.4 and 1 km from the original position investigated respectively. However, no explanation or further comment is made.

Post-processing of magnetic data was achieved by applying a set algorithm in *Microsoft Excel* to remove diurnal variations and ‘zero’ all values so that dipole anomalies register positive and negative values. The nature of the algorithm is detailed and it is stated that the contractors have used it extensively for five years. Magnetic data were then gridded into contour maps using *Bentley's Geopak* software. Such contour plots are provided for each site where magnetic anomalies were encountered.

Wrecks on the Seabed Round 2: assessment, evaluation and recording - geophysical survey report

(Wessex Archaeology 2006a)

One of the objectives of this project was to refine and develop methodologies related to area survey methods and the survey of ephemeral sites.

Accordingly, an area 2km square was surveyed using 25m run line spacing and a Geometrics G-881 magnetometer with depth sensor. The sample rate used is not stated. The survey vessel was positioned using RTK GPS. Multi-beam bathymetric data was collected for the area.

Each run line was surveyed twice using 'deep' and 'shallow' towfish depths. Neither towfish altitude nor water depth is stated although a difference of up to 10m is stated between 'deep' and 'shallow' tows. The collected data was post-processed in *MagPick* software. Data was selectively interpreted to simulate different surveys using 25/50/75 and 100m run line spacing. Each using both 'deep' and shallow' tow.

Time series plots and interpolated surface plots were used to identify magnetic anomalies. The targets identified within each of the contrasting data-sets are then summarised in a table and discussed comprehensively.

Salcombe Cannon Site, Devon: designated site assessment report

(Wessex Archaeology 2006b)

This is a report on a marine magnetic survey of the designated Salcombe Canon Site. The magnetometer data was collected using a Geometrics G-881 Caesium Vapour sensor using 10m line spacing. It is inferred, but not explicitly state, that an RTK GPS system is used for positioning the survey.

Each line of magnetometer data was processed to remove regional and diurnal influences, before being plotted and interpreted as a contour map with field strength values represented by colour bands. Thirty nine anomalies are identified, however all but two are attributed to geological features. Only these remaining two anomalies are recommended for further investigation. The report does not state instrument altitude or sample rate and water depth is inferred but not stated.

Gull Rock, off Lundy Island, North Devon: designated site assessment: report

(Wessex Archaeology 2009)

This is a report on a marine magnetic survey of the Gull Rock, a protected wreck site. The magnetometer data was collected using a Marine Magnetics SeaSpy Overhauser sensor, operating at 4Hz, and was recorded in Hypack. The survey vessel was positioned using RTK GPS, the magnetometer used a depth sensor to log instrument depth and 10m line spacing was used. Each individual run line was recorded as a separate *x,y,z* ASCII file.

Each run line was processed in MagPick software to correct for layback and remove regional and diurnal variations. The data were then plotted and interpreted as a contour map with field strength values represented by colour bands. Only magnetic anomalies with a deflection greater than 5nT were recorded.

	Instrument	Sample Rate	Runline Spacing	Position Fixing	Deployment	Acquisition Software	Altimeter/ Depth Sensor	Water Depth	Fish Altitude	Anomalies Identified	Anomalies Investigated
Median Deep Area 461	Overhauser	Not stated	115m	Differential GPS	Tow	Not stated	Not stated	35-45m	Not stated	2	0
HMS *Colossus* Debris Field 2005	C. Vapour	Not Stated	15m	EGNOS GPS	Tow	Site Searcher	Depth Sensor	10 -20m	7 -16m	291	103
HMS *Scylla* 2004	Proton	Not Stated	50m	Not Stated	Tow	Graphic Print	No	<25m	<25m	4	0
South West Wave Hub 2006	Overhauser	Not Stated	75 & 100m	RTK GPS	Tow	Not Stated	Not Stated	0 -60m	<57m	Not Stated	0
Falmouth Cruise Project 2008	C. Vapour	10 Hz	10m	RTK GPS	Tow (36m)	Hypack	Depth Sensor	6-12m	4-6m	Not Stated	9
Boyce *et al (2004)*	Overhauser	4 Hz	10 – 20m	DGPS	Tow (20m)	Not Stated	Depth Sensor	4 – 10m	2 – 8m	n/a	n/a
Wrecks n the Seabed Round 2 2006	C. Vapour	Not Stated	25m	RTK GPS	Tow	Not Stated	Depth Sensor	Not Stated	10m	8	0
Salcombe Cannon Site 2006	C. Vapour	Not Stated	10m	RTK GPS	Tow	Not Stated	Not Stated	<25m	Not Stated	39	0
Gull Rock 2009	Overhauser	4 Hz	10m	RTK GPS	Tow (80 - 200m)	Hypack	Depth Sensor	Not Stated	Depth: 5 – 18m	Not Stated	Not Stated
Enright *et al (2006)*	Overhauser	1 Hz	10m	DGPS	Tow (30 – 120m)	HydroPro	Not Stated	7 – 37m	5 – 22m	11	11

Fig 2 Summary and comparison of survey reports

Only one magnetic anomaly was identified and this was considered to be of modern origin and not of archaeological interest. It is stated that the Gull Rock site lies over igneous substrate which can be magnetic and which can mask small archaeological targets. It is observed that the magnetometer data show a number of 'dykes' running through the site represented by broad positive monopoles.

The report does not state instrument altitude and water depth is inferred but not stated.

3.3.4 Conclusions

This review is not intended as an exhaustive study of marine magnetometer survey and reporting practices. The selection of discussed survey reports was dictated by what was readily available. However, the sample of reports reviewed here does indicate the range of survey methodologies and reporting practices in use. It is apparent that certain important aspects of the survey methodologies, particularly fish altitude and run line spacing, are not always suitably designed for archaeological appraisals. A good example of this is the report on Median Deep (detailed above in section 3.3.2). Here the tow fish altitude is not stated but given the run line spacing (115m) and the stated water depth (36 to 44m BCD), the two magnetic targets identified will be considered. The targets exhibited a deflection of 8 and 12 nT and the cut-off deflection for target selection is stated as 5nT. This gives an approximate minimum target detection of 150 tonnes of iron for targets situated between run lines and 21 tonnes for targets lying directly under a run line (assuming a tow fish altitude of 35m). This also amply demonstrates the large differential sensitivity when using large run line spacing – as discussed in section 3.6.1.

It is also apparent that magnetic surveys are not always designed solely for archaeological purposes – in these cases compromises may be inevitable. Our own experience has shown that survey data may have already been collected by the time the archaeologist becomes involved in the project. What is important is that the limitations of a data set or survey methodology are understood and clearly stated in the report – which should in any case state the likely minimum mass of iron which can theoretically be detected by the survey – and thus what will not be detected by the survey.

3.4 Performance of magnetometers

3.4.1 Magnetometer types

This section discusses the different types of total field marine magnetometers which are available to hire or buy in the United Kingdom. Several authors outline the improved performance available by using gradiometers, which consist of two or more total field magnetometers fixed at set distances apart (see below Section 3.4.5). There are three main types of marine magnetometers currently available.

3.4.1.1 Proton precession magnetometers

Until relatively recently these were common in magnetic surveys but they have now been largely replaced by improved instruments. They are however still available, and despite their limitations may have a role to play where the expected target size is relatively large, where the water depth is shallow and where cost is an important issue. There is a considerable body of 'legacy' magnetic survey data collected using this type of magnetometer.

Their main characteristics are that they are relatively inexpensive and have a sample rate of between 0.5 to 2 readings per second. Their sensitivity is typically 0.2nT to 1nT and they are sensitive to heading errors (Dix *et al* 2008). Their main disadvantage is the relatively low sample rate and higher signal to noise ratio.

An example of a proton precession magnetometer available in the UK is the Planet Electronics (UK) MX500 unit. Planet Electronics claim a data rate of 0.3 to 2 readings per second with a 'resolution' of 0.5nT. It should be born in mind that sensitivity in this type of instrument decreases as data rate is increased (see below, section 3.4.4). The cost of this unit is currently £3,500, putting it within the reach of small archaeological groups and societies. Interestingly, this unit is also offered as a two-sensor gradiometer including software and sells for £7,000.

3.4.1.2 Overhauser magnetometers

This is an improved type of proton precession magnetometer. It has improved signal to noise ratio, with a typical sensitivity of 0.015nT/ $\sqrt{\text{Hz}}$ (where the frequency in Hz is determined by the sample rate) and an absolute accuracy of 0.1 to 0.2nT. They also have an improved sampling rate of between 1 and 5 readings per second. This type of instrument is also subject to lower heading errors and requires less power than conventional proton precession magnetometers (Dix *et al* 2008). This type of instrument has been used in a number of archaeological magnetic surveys, for example Wessex Archaeology (2009) and Camidge *et al* (2006). The extent to which the sampling rate affects noise and sensitivity is difficult to determine from the published literature, it seems likely however that increased sampling rate will lead to lower sensitivity (see below Section 3.4.2).

Two Overhauser magnetometers are currently available from hire companies in the UK; both instruments are manufactured by Marine Magnetics (Canada). These units are the SeaSpy and Explorer magnetometers, and they have similar specifications except for their physical size and depth ratings. The cheaper Explorer is not available with the optional sonar altimeter. The specifications which Marine Magnetics claim for these units are summarised in Figure 3.

	Explorer	SeaSpy
Accuracy	0.1 nT	0.1 nT
Sensitivity	0.02 nT *	0.01 nT *
Resolution	0.001 nT	0.001 nT
Sample rate	4Hz – 0.1Hz (from 1 reading every 10 seconds to 4 readings per second)	4Hz – 0.1Hz (from 1 reading every 10 seconds to 4 readings per second)
Heading error	Not stated	Zero
* No data rate specified		

Fig 3 Manufacturers' specifications for SeaSpy and Explorer magnetometers

These instruments offer better signal to noise ratios than proton magnetometers with improved data rates. It is not possible to determine how much the sensitivity is affected by using the higher data rate from the available literature. The Explorer currently sells for about £12,000 while the SeaSpy costs about £17,000. A gradiometer version is also offered by Marine Magnetics, a two-sensor system at $70,000 and a three-sensor system at $78,000.

3.4.1.3 Optically pumped magnetometers

These offer the highest specification of the types under consideration. Sensitivity is 0.004nT/$\sqrt{\text{Hz}}$ with absolute accuracy of <2nT, sample rates can be as high as 20 readings per second (Dix *et al* 2008).

There are a number of different types of optically pumped magnetometers. However, the only type currently available for marine use in the UK hire pool is the caesium vapour magnetometer. These are principally manufactured by Geometrics (USA), the now discontinued G881 and the replacement model G882. These are the most expensive of the magnetometers considered at over £20,000 per unit.

Geometrics G882 – claimed specifications	
Accuracy	< 2 nT
Sensitivity	< 0.004 nT/ $\sqrt{\text{Hz}}$ RMS
Sample rate	Up to 20 per second
Heading error	±1 nT

Fig 4 Manufacturers' specifications for the Geometrics G882 caesium vapour magnetometer

They offer the best sensitivity and data rate of all the available instruments. A gradiometer version is also offered by Geometrics, this consists of two G882 magnetometers in a horizontal configuration, it is designated the G882 TVG. No price was quoted for this unit, but the price of the individual G882 units suggests that it will be over £40,000.

3.4.1.4 Discussion

The majority of the literature recommends the use of caesium vapour magnetometers for use in marine archaeological surveys. The caesium vapour magnetometer is specified in the minimum requirements for archaeological survey (Dix *et al* 2008). '*Today state-of-the-art magnetometers use caesium vapour or hydrogen (another optically pumped magnetometer) ... for high sensitivity and very low noise*' (MMS 2004, 18). 'Use Caesium gas or equivalent system capable of resolving anomalies of 5 nT and above' (WA 2007). '*Caesium magnetometers or Overhauser proton precession magnetometers provide sufficiently high quality data for archaeological use'* (WA 2004).

It is fairly clear that in theory the caesium vapour magnetometer is probably the best readily available total field marine magnetometer for use in archaeological surveys. It is this type which was recommended by Dix *et al* (2008). The Overhauser magnetometer may in practice offer similar results, albeit at a lower data rate (4Hz). There may be issues of loss of sensitivity with increased data rates; this could not be fully resolved from the available literature. This area needs to be investigated in practical trials under controlled conditions. This issue needs to be resolved as Overhauser instruments are regularly used in commercial archaeological surveys.

3.4.2 Sample rate

The geomagnetic field strength varies spatially and over time as a continuous, smooth function. A magnetometer will periodically measure and report the value of the geomagnetic field at a particular instant and the frequency with which the measurements are made is known as the sample rate or update rate. The maximum sample rate achievable depends on the type of magnetometer being used and for many instruments the rate can be altered. The sample rate used for a survey affects the density of measurements recorded as the magnetometer moves over the survey area and this affects the minimum size of target that can be detected.

Proton magnetometers use a two-stage polarise and sample approach to measuring the magnetic field so the maximum sample rate is limited to the speed at which these two steps can happen. Typical useable sample rates for a proton magnetometer are between 0.3Hz and 2Hz. Much of the time is taken up in the polarising phase and for these instruments the sensitivity increases as the polarising time increases. The result is that proton instruments become more sensitive as the sample rate decreases. Caesium and Overhauser magnetometers can make field measurements continuously so sample rates up to 10Hz can be used.

Higher sample rates result in higher density of data recorded during the survey, the higher the data density the more faithfully the sampled values represent the actual variations in the magnetic field strength. The data density is a measure of the density of the measurements made along any survey run measured in samples per metre. If we consider a magnetometer being towed behind a boat, the sensor will be moving forward and periodically making a measurement of the magnetic field strength. Increasing the speed of the vessel will move the sensor further between measurements and so decrease data density. Increasing the sample rate will reduce the distance between measurements and increase the data density. To increase the data density it is better to run survey lines slowly using a magnetometer with a fast sample rate. The data density is important as the density of the measurements sets the lower limit on the size of target that can be detected, both in terms of its physical size and in terms of the field strength. At this point we need to consider what constitutes a 'target' and how they can be detected.

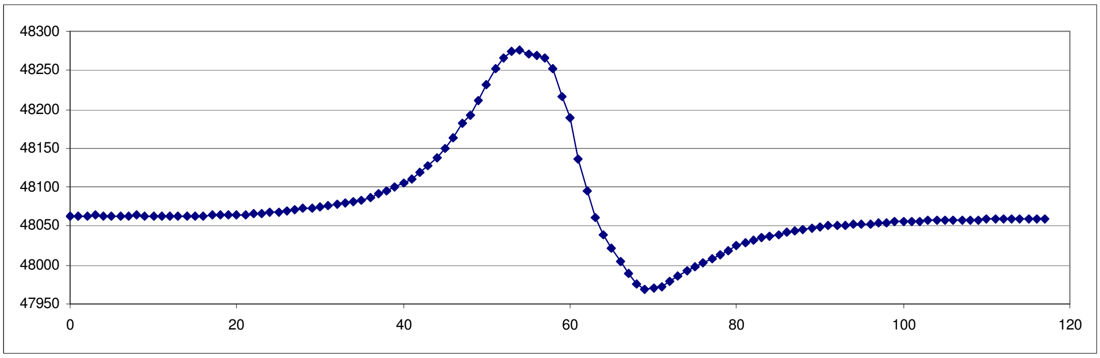

Figure 5 Time-series plot of a magnetometer anomaly

We can recognise the deflection on the graph (Fig 5) as a well-defined anomaly as the measurements vary smoothly from the average background value over a number of measurements. If we now reduce the number of measurements made over that signal by towing the sensor faster or reducing the sample rate we can see that the anomaly becomes less easy to identify. Eventually it becomes impossible to distinguish the anomaly from a single mistake, a spike in the measurements. Figure 6 below shows a sequence of traces with ever decreasing sample rate with the upper plot A sampled at 10 Hz and the anomaly clearly defined. Dropping the sample rate to 5 Hz makes little difference on an anomaly of this size as shown in the second plot B. In the third plot C the data is sampled at 1 Hz, the anomaly shape can still be made out but now only across five samples. Sampling once every three seconds in plot D shows the anomaly as a single peak not easily differentiated from spike noise, rates this low are often obtained from proton magnetometers using a two second polarisation time. The exact time-width of an anomaly depends of course on the target dimensions and the tow speed.

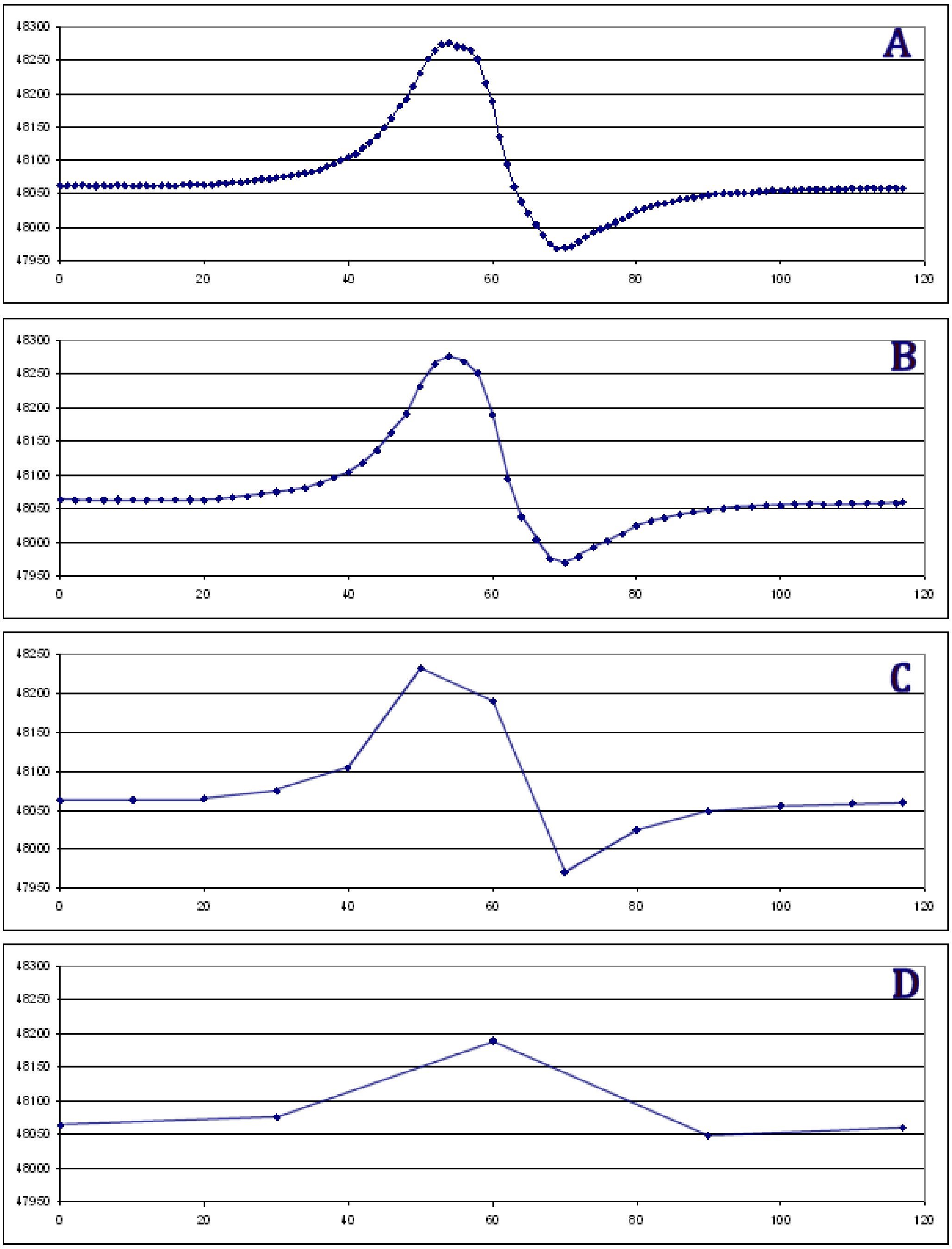

Fig 6 The effects of sampling the same anomaly at 10 Hz, 5 Hz, 1 Hz and 0.3 Hz. X axis in seconds

The same occurs if we consider the physical size of a target. The magnetic effect of small targets is largely confined to the immediate area of the target itself because the field effect decays with the cube of the distance away from it. We can see above that we need to make a minimum number of measurements over a target before it can be detected so if the data density is too low the target may only be registered on one measurement and could be interpreted as noise.

For the majority of survey work the data density in the direction of tow (inline) is far greater than the density in the direction 90° to the tow as this is defined by the runline spacing. In practical terms the minimum size of target that can be detected is determined more by the runline separation and achievable position accuracy.

3.4.3 Sensitivity

Figure 7 shows the sensitivity of the main types of marine magnetometer as stated in Dix *et al* (2008). These values accord well with those claimed by the manufacturers – see above magnetometer types, Section 3.4.1. Although the caesium vapour magnetometer has the best claimed/theoretical sensitivity the actual relative performance needs to be established under controlled conditions, especially as the data rate used has an effect on sensitivity – for discussion of this see above sample rate, Section 3.4.2.

Type	Sensitivity	Max sample rate
Proton precession	0.2nT to 1nT	2 Hz
Overhauser	0.015 nT/ $\sqrt{\text{Hz}}$	5 Hz (4 Hz for Explorer & Seaspy)
Caesium vapour	0.004 nT/ $\sqrt{\text{Hz}}$	20 Hz

Fig 7 The sensitivity of the main types of marine magnetometer as stated in Dix et al (2008)

Sensitivity concerns the relative size of the magnetometer signal and the noise or readings caused by factors other than the target, this is referred to as the signal to noise ratio. To improve the signal to noise ratio we need to maximise the signal caused by the target (get the magnetometer closer to the targets/seabed) and minimise the noise (see below, Sections 3.6.1 and 3.9.1 respectively).

Does the sample rate affect sensitivity or noise levels?

We have been unable to find any information in the published literature concerning the effect of sample rate on sensitivity or instrument noise levels. However, hearsay evidence suggests that increasing instrument sample rate may increase noise levels and thus cause a reduction in sensitivity – as any deterioration in the signal to noise ratio will reduce the size of target that can be reliably detected. Accordingly a manufacturer of each of the principal types of marine magnetometers was contacted concerning the effect of sample rate on the sensitivity of their instruments. To date replies have been received from Planet Electronics (MX500 proton precession magnetometer) and Geometrics (G882 caesium vapour magnetometer). We are awaiting a reply from Marine Magnetics (Explorer and Seaspy Overhauser magnetometers).

Communications with Ross Johnson of Geometrics Ltd:

The following statements all indicate that sample rate does affect signal to noise ratio in the G882 magnetometer, '*Very high speed sampling tends to lower the signal to noise ratio*' and '*..increasing the sample rate by a factor of four will increase the noise in the data by a factor of two*' and '*very high speed sampling tends to lower the signal to noise ratio*'. However it is claimed that this makes no practical difference at data rates of 10Hz and less. Thus it is acknowledge that at the highest data rate of the G882 there is a loss of sensitivity.

One final comment should be treated with some caution as it refers to instrument types made by Geometrics' competitors, '*Proton and Overhauser magnetometers will claim they sample more quickly than 1 or 2Hz, but our experience is that they get very noisy at higher sample rates*'.

Communications with Bob Hickson of Planet Electronics Ltd, '*You are correct that with a proton magnetometer if you increase the sample rate the absolute sensitivity will decrease. This is because the signal generated by the magnetic sensor requires a certain amount of time to polarise the protons. This time, is dependent on the liquid used to generate the signal, for most hydrocarbons it's about 3 seconds to gain the maximum signal, if the polarisation is shorter then the signal level generated is less and hence the signal to noise ratio is lower. The answer to your question is however, not so simple, provided the signal to noise ratio is sufficient to achieve the desired sensitivity, then from the users point of view there does not appear to be any loss of sensitivity when the sample rate is increased*'.

Once again the effect is acknowledged, and dismissed as of no practical significance by the manufacturer. What is clear is that there is probably an increase in noise as the instrument sample rate is increased. The magnitude and nature of this increased noise needs to be established for each of the principal marine magnetometer types under controlled conditions so that the effect of data rate on sensitivity can be properly understood. Any difference in the noise levels may also result in a difference in the smallest detectable anomaly for different instruments (see above, Section 3.2.6). Understanding the differences in different instrument types at different data rates will allow the data rate to be optimised for specific survey requirements.

3.4.4 Closest approach

The caesium and proton magnetometers most often used for marine magnetic surveys are omni-directional sensors so the relative position of any anomaly cannot be determined directly from a single series of measurements. A target will cause nearly the same signal response if it lies to the left, right or below the sensor as the sensor passes by so long as the distance from target to sensor remains the same. Only if the magnetometer passes closely will differences between the positive and negative bipole anomaly become apparent.

We can limit the estimation of target position somewhat for marine surveys. The magnetometer is usually towed through the water and the targets lie on or in the seabed, so it can be assumed that the targets will lie somewhere below the sensor. The motion of the sensor through the resultant magnetic field caused by the target gives a series of measurements as the sensor passes by the target. Plotting these measurements gives a set of characteristic curves that indicate the position of the target in the cross-line direction, the direction at 90 degrees to the direction of sensor motion (see below, Sections 3.5.2.8 and 3.5.3.1).

The position of the target reported by the magnetometer is the position of closest approach and not necessarily the actual position of the target itself. The target may lie to the left or right of the line or may lie directly below it and from a single line it is not possible to determine which. The same target may be detected on the adjacent survey lines run either side of this line in which case a better estimate of position can be made by looking at the relative size of the signals detected on each line. Smaller targets may not be detected on any other adjacent runlines so to estimate a more accurate position a cross-line should be run at 90 degrees to the original line through the point of closest approach.

3.4.5 Single sensor vs. gradiometer

Total-field magnetic data collected using a single sensor have been used in maritime archaeological prospection for decades (eg Arnold 1981). One problem which is apparent when using such data is the difficulty of separating archaeological anomalies from regional and diurnal variations in the earth's ambient magnetic field (Hrvoic and Pozza 2004). Some methods of doing so during post-processing of total-field magnetic data are described below in Section 3.9, however magnetic gradiometers can be used to collect data that do not need such processing (Hrvoic and Pozza 2004).

Magnetic gradiometers consist of two sensors separated by a fixed distance, each recording the magnetic field simultaneously. The difference between the values measured by each sensor is referred to as the 'gradiometer signal' and as such the difference is expressed in nT. Alternatively, the gradiometer signal may be divided by the sensors' separation to give an approximation for the gradient of the magnetic field (Hrvoic and Pozza 2004). How closely this approximates the gradient depends on the depth and dimensions of the causative feature compared to the sensor separation. For example, a gradiometer with a sensor separation of 1m measuring at an altitude of 6m above the sea floor is a poor approximation for the gradient. As the separation of the individual sensors determines the relative contribution of near and distant magnetic sources, the closer the sensors are mounted together the greater the reduction of the background signal. However, more of the archaeological signal will also be lost (Aspinall *et al* 2008, 33).

Depending on the arrangement of the two sensors the gradient of the magnetic field in a particular direction is measured. Two magnetometers above each other measure the vertical gradient; two magnetometers 'behind' each other measure a horizontal gradient. The exact alignment of the horizontal sensor array with respect to magnetic north (its attitude) determines the contribution from the north and west components of the field gradient vector, respectively. This means that even a slight change of the angle of attitude leads to an undesirable change in the horizontal gradiometer signal. In addition, the attitude of a towed sensor array may deviate from the direction of the path of the survey vessel as underwater currents may lead to additional forces. Such changes are difficult to determine but may have considerable influence on the resulting data. The only reliable solution to this problem is the use of two perpendicular horizontal gradiometers with an accurate measurement of their attitude (eg with an electronic compass). This way the north and the west component of the horizontal gradient can be accurately determined, regardless of the attitude of the gradiometer array. To measure all three gradient components requires the use of four magnetometers.

As the effect of any diurnal influences upon the total-field will be recorded simultaneously by each sensor, such variations will be removed from the gradiometer data-set (Wald and Cooper 1989, 22). Similarly, the influence of geological features upon the magnetic data-set will be reduced as such deeply buried material tends to exert a broad influence upon the total-field resulting in very similar measurements from each sensor (Aspinall *et al* 2008, 33, Hrvoic and Pozza 2004).

The horizontal gradient in tow direction is sometimes approximated by subtracting the difference of readings from a single magnetometer at two subsequent times and dividing by the distance it has travelled. However, the earth's magnetic field may have changed slightly even over such short time interval and the calculated gradient must hence be considered as just an estimate of the real gradient value determined at a single time.

Gradiometers also have other reported advantages over single sensor magnetometers. Aspinall *et al* (2008, 76) demonstrate that they are better able to resolve individual magnetic sources in close proximity to each other. They also provide an opportunity for accurate position estimations to be made (as discussed below in Section 3.9.4) for small targets visible on only a single run line (Kearey *et al* 2002, 164).

Hrvoic and Pozza (2004) state that gradiometers which consist of only two sensors can create data-sets which are harder to interpret than total-field measurements. As which component of the magnetic gradient being mapped (x, y or z) is determined by the relative alignment of the two sensors, magnetic structures oriented in certain directions will be enhanced. This is undesirable in small target surveys.

Although marine archaeological surveys have been conducted using gradiometers (eg Weiss *et al* 2007) their use in marine archaeology is far less advanced than is the case in terrestrial archaeology. The effectiveness of marine gradiometers in high resolution small target surveys is evidenced by their use in the detection of submerged unexploded ordnance (eg Pozza *et al* 2003). However, the gain relative to the expense of hiring multiple sensors as well as the possibility of more complex data-sets is hard to establish due to the present lack of available survey reports and data-sets. Gradiometer arrays may be more subject to tidal flow disturbance due to the larger drag brought about by the frame and multiple sensors.

3.4.6 Heading error

Intensity measuring magnetometers (Total Field Magnetometers) ideally measure the strength of the ambient magnetic flux density, regardless of the relative orientation between sensor axis and direction of the magnetic field. However, in practice there is a slight dependency and this is referred to as 'heading error'. Linked associated effects are 'dead zones' which are ranges of sensor orientations in which no useable signal can be measured.

Not all manufacturers are very specific about the heading errors of their sensors and the following list is hence only an approximation.

Sensor Type	*Manufacturer*	*Sensor*	*Heading error*	*Dead Zones*
Proton Precession	GEM	GSM-19T	Minimal	?
	Geometrics	G-856AX	?	±40°
Overhauser	Marine Magnetics	SeaSPY	None	None
	GEM	GSM-19	None, virtually none	None
Caesium Vapour	Geometrics	G-881	±1 nT (over entire 360° spin and tumble)	<15° and >75°
		G-882A	±0.15nT (over entire 360° equatorial and polar spins)	<15° and >75°
		G-858	< ± 0.5 nT	?

Fig 8 Heading errors of different sensor types

The reasons for the instrument-specific heading errors and dead zones are related to the quantum mechanical properties that are used for measurement of the magnetic flux density. In proton magnetometers, the polarisation of the protons by an external field has to be in a direction different from the ambient field to be measured. Otherwise the depolarisation stage of the measurement cycle will not lead to a precession of the proton spins about the axis of the ambient field. If the axis of the polarising coil is aligned with the ambient field no measurement signal is obtained. As the angle is gradually increased to 90° the polarisation becomes better and the signal-to-noise ratio improves. Importantly though, if a precession frequency can be measured at all, it will always represent the true magnetic flux density. Poor orientation will hence deteriorate the signal but not alter the value of the measured magnetic flux density. The heading error for proton magnetometer is hence sometimes quoted as 'none' or 'minimal'. Somewhat confusingly, it appears that the polarising coil of some proton magnetometers is not aligned with the cylinder that forms the sensor but is perpendicular to it. This is inferred from the manual for the Geometrics G-856AX Proton Magnetometer:

> *In regions were the magnetic inclination is greater than +/-40°* [e.g. vertical]… *the sensor should be mounted so that its cylindrical axis is vertical. … Aligning the sensor this way will place the axis of the sensor's internal coils perpendicular to the Earth's field and produce optimum signal* (Geometrics 2007).

The Overhauser magnetometer uses a RF-polarised electron assemblage to subsequently polarise the protons prior to their depolarisation precession. It is unclear from the available literature exactly in which direction the protons will be polarised. However, as these sensors do not require a solenoid for polarisation it is conceivable that there is indeed no heading error and no dead zone, as stated by the manufacturer.

The strongest heading error and most severe dead zones of the discussed intensity measuring instruments is found in the Caesium Vapour magnetometers. The magnetic field is measured as the Zeeman split in the Caesium's atomic energy spectrum (Aspinall et al 2008). Polarised light is used to probe this Zeeman split and the relative orientation between the ambient field and the direction of the optical filters that generate the polarisation (i.e. the direction of the sensor axis) has an influence on the Zeeman split. Caesium energy lines, in contrast to other alkali vapour elements like Potassium, overlap broadly when split by the encountered ambient fields and this leads to noticeable heading errors and considerable dead zones. Geometrics specify for the G-881 Caesium magnetometer the equatorial and polar dead zones (Geometrics 2001):

> *The sensor head should be oriented so that the earth's field vector arrives at an angle of from 15° to 75° to the optical axis of the sensor, for all towing attitudes.*

It is worth noting that there have been elaborate claims and counter-claims about heading errors of Caesium and Potassium magnetometers by their respective manufacturers, both on the web and in the scientific literature. Broadly evaluating these, the instrument specifications quoted by the manufacturers appear to be reliable.

In addition to these sensor specific heading errors, which cannot be avoided by the user, there may also be external heading errors due to the assembly of a tow-fish. If metal components with even a slightly increased magnetic susceptibility are mounted next to a magnetometer, their small magnetic effect, induced in the ambient magnetic field, will be different depending on the relative orientation. For example, the components may be positioned north of the sensor when towing west to east, but will be south of the sensor when towing east to west. Therefore, changing the towing direction of the magnetometer will change the measured magnetic signal. Most manufacturers are clear in their manuals about the dangers of such magnetic contamination but the effect of magnetic inclusions is often underestimated (for example in what is deemed a non-magnetic 'brass' screw).

Heading errors may manifest themselves in the collected data as slight differences in magnetometer readings depending on the tow-line direction. These may possibly be adjusted through methods similar to the compensation of diurnal changes, for example by using tie-lines. Heading errors may also introduce noise in the data if the orientation of the tow-fish deviates slightly and inconsistently from the tow direction, for example due to underwater currents.

3.5 Targets and signals

3.5.1 Expected archaeological targets

3.5.1.1 Introduction

Although magnetometers are capable of detecting deflections in the earth's magnetic field caused by various materials, the practical application of magnetometers in marine archaeology is mainly limited to the detection of ferrous objects. Iron has been used in the construction and fitting of vessels for several millennia.

Below is an outline of typical archaeological targets which might be encountered during a marine magnetometer survey. In addition to these targets debris such as trawl wire, mooring chains, compressed-gas cylinders, munitions and so forth can be expected in varying numbers depending upon the nature of the survey area.

3.5.1.2 Modern vessels

Throughout the 19th century commercial vessels constructed of iron rather than wood became increasingly commonplace and with the development of explosive munitions navies began to adopt the new technology. From 1885, steel had become the principal material employed in ship construction (Kemp 2002, 128-140, 172).

The size of boats and ships of ferrous construction built and sank over the past 150 years covers a considerable range, from the largest 500,000 DWT Ultra Large Crude Carriers (ULCCs) to small fishing boats. Most are of ample size to effect a significant deflection in the Earth's magnetic field and are often characterised by a complex of dislocated anomalies.

In addition to vessels with steel hulls, vessels of wood, fibreglass or aluminium construction are often detected during marine magnetic surveys due to the presence of iron machinery.

The majority of modern shipwrecks are casualties of the First and Second World Wars, with over 7,500 merchant vessels known to have been lost by Britain alone (Tennent 1990, MoD 1989). Of these, the bulk were lost to U-Boats operating in the Atlantic. In the course of inflicting such devastating damage to allied shipping Germany lost 959 U-boats (MoD 1990), a remarkable number compared to the 171 HM submarines lost between 1904 and 1971 (Evans 1986). Although considerably smaller then contemporary naval and merchant ships a WWII U-boat, typically ranging between 300 - 2000 tonnes displacement (MoD 1989, McCartney 2003), would be expected to effect a detectable deflection in the earth's magnetic field.

Although not an immediate concern when considering potential marine archaeological targets, the possibility of encountering aircraft remains in the marine environment should not be discounted. In view of their place in living memory English Heritage (2002) stresses the archaeological importance of aircraft remains in both the terrestrial and marine environment. Furthermore, such remains have been encountered in the course of marine aggregate extraction (WA 2008). Due to its low weight comparative to ferrous metals aluminium has been employed in aircraft design since the Wright brothers' first flight in 1903 (Kennedy *et al* 1960). As aluminium is not a ferromagnetic material the chance of observing even consolidated aircraft remains in the course of marine magnetometer surveys is limited, as discussed by Weiss *et al* (2007). Conversely, aluminium is a very effective sonar reflector and, if exposed, is most likely to be detected in the course of a side scan sonar survey.

3.5.1.3 Anchors

Few vessels would leave shore without carrying at least one anchor; the size, shape and construction of which is heavily dependent upon its antiquity and the vessel from which it came. An anchor's efficiency is served by its weight as well as its design and as such they often constitute one of the largest and most robust artefacts associated with a wreck event. The use of iron anchors is evidenced as early as the 3rd century AD (Jobling 1993, 11).

Iron anchors can range in weight from tens of kilograms to tens of tonnes (Jobling 1993; Curryer 1999), with anchors of three tonnes in common use by the Royal Navy during the 18th century (Steel 1794 cited in Jobling 1993, 113). Anchors are principally T-shaped although those with iron stocks, which were in common use from the 18th century (Curryer 1999, 108), are better described as H-shaped. Anchors can be expected to be of wrought iron construction up until 1900 after which steel would have been used (Curryer 1999).

Anchors are typically found occupying one of two positions, either lying prone on the seabed or with one arm fouled and the other standing near vertical (Camidge and Witheridge 2005; Camidge and Randall 2009). They are often found as isolated artefacts, when they have perhaps been fouled and abandoned, and are also of course found in association with shipwrecks.

In the latter instance it is common that more than one anchor would have been aboard the vessel. A 74-gun ship-of-the-line, one of the commonest naval ships of the 18th century, would have carried six anchors (4 Bower, 1 Stream, 1 Kedge), totalling some fifteen tonnes in weight (Steel 1794 cited in Jobling 1993, 113).

Ferrous chain is often found in association with anchors and will add to the mass of such a target. Chain can vary in form considerably, from long and thin when laid out on the seabed to a large mass when coiled.

3.5.1.4 Ship's ordnance

Since the development of the first ship's gun in the 15th century (Kemp 2002, 64) ships ordnance has served an important role aboard vessels of war and, until the 20th century, vessels of trade such as those of the East India Company (Kist 1988; Rhynas Brown 1990). Similarly to anchors, the size and number of guns carried by a vessel was heavily dependent upon its antiquity, size and function. However, the largest ship's gun commonly used during the hey-day of sail was the 32lb, which weighed in the region of three tonnes. Conversely, the smallest ship's gun in common use was the 3lb Minion, of 350 kilograms (Lavery 1987, 99, 103).

Until the advent of iron frames and hulls ordnance constituted the largest source of iron material aboard a vessel of war. The 74-gun ship-of-the-line carried over one hundred and fifty tonnes of iron in the form of guns and up to a further fifty tonnes of ammunition (Caruana 1997, 137, 112).

They are commonly found lying prone on or under the seabed, although they have also been found standing near vertical, muzzles buried in sand (Camidge 2002:13). Early ships' guns were typically constructed from several wrought iron elements. However from the 17th century to the introduction of steel in the late 19th century ships' guns were predominantly of cast iron

Individual items of ammunition, even a 32lb (14kg) round shot, are unlikely to be detected in the course of a marine magnetic survey (see below, Section 3.6.1). However, clusters of round shot have been known to produce detectable anomalies at a distance of 12m from the magnetometer (Camidge and Witheridge 2005, 31).

Modern ordnance and munitions range considerably, from First and Second World War naval mines to shells and bombs. Such material may be detected in the debris field of wrecked vessels or as isolated phenomenon and, despite possible archaeological or historical interest, must first be treated as a serious potential hazard. The detection of un-exploded ordnance (UXO) is a specific and specialised sub-discipline of marine magnetometry, which is responsible for much research and development into related technology and data interpretation techniques.

3.5.1.5 Fastenings, fixtures and fittings

Iron fastenings are known to have been used in boat construction as early as the 4th century BC (McCarthy 2005, 30). The low mass and wide dispersion of fastenings on early vessels are unlikely to be detected during a marine magnetic survey at the instrument altitudes typically employed. However, the combined mass of the larger iron bolts used to fasten together the frames of later carvel constructed vessels (Lavery 1987, 65) present a more realistic, if optimistic, target.

Moreover, the use of iron in the fixtures and fittings aboard post-medieval vessels is well attested if difficult to quantify. Capstans, pumps, rudder gudgeons, ballast and a whole host of other objects integral to the construction and running of a wooden vessel can be seen to be made in part or in whole of ferrous material (Goodwin 1987; Lavery 1987; McCarthy 2005).

The accumulative mass of such objects is as hard to predict as it is to account for. A geophysical survey of the designated stern site of HMS *Colossus*, the Isles of Scilly, produced a magnetic anomaly for the main site which indicates the presence of twenty-two tonnes of ferrous material (Camidge and Witheridge 2005, 16; using Hall's equation). The principal quantifiable iron on the site are the six 18lb guns which, weighing two tonnes each (Lavery 1987, 99), can be seen to account for little more than half of the ferrous material indicated by the magnetic anomaly. The remainder can only be accounted for by the mostly amorphous ferrous concretions present on, and below, the seabed.

3.5.1.6 Non-metallic Targets

Although the application of magnetometers in marine archaeological surveys is generally discussed in terms of detecting ferromagnetic metals, magnetometers are able to detect deflections in the ambient magnetic field resulting from non-metallic, ferromagnetic influences. Studies which demonstrate the efficacy of employing magnetometers in the investigation of non-metallic archaeological targets in the marine environment have been conducted., such as Boyce *et al* (2004) - discussed in section 3.3.3 above - and Green *et al* (1967).

Boyce *et al* (2004) report magnetic anomalies ranging from 3 – 10nT, resulting from a significant mass of submerged hydraulic concrete, which contains a significant volume of ferromagnetic volcanic ash and tuff. However, these anomalies were observed in data collected with a maximum reported instrument altitude of 8m and which had undergone extensive post-processing. Diurnal variations were recorded via a shore mounted base station and draping (see Section 3.9.1.4) of the data was used to account for variations in magnetometer altitude.

Green *et al* (1967) reports the findings of a thorough magnetometer survey conducted over a 4^{th} century BC shipwreck consisting principally of an amphora mound measuring 3 x 5m. The reported findings detail that certain of the observed magnetic anomalies were affected by the magnetic properties of the amphora themselves. Notably the magnetometer survey was undertaken using a diver positioned instrument, which was laid on the seabed and readings collected at 2m intervals. Green *et al* demonstrate that, considering the low amplitude of the anomalies recorded in this fashion, the detection of the wreck using a surface-towed instrument was not considered practicable.

Although these two studies admirably demonstrate the efficacy of employing marine magnetometers in the investigation of known, non-metallic archaeological features, it remains to be demonstrated that such sites are likely to be detected by anything other than the most vigilant of large area surveys.

3.5.1.7 Conclusions

It is clear that the range of archaeological targets which might be encountered during a marine magnetic survey spans as significant an array of forms and masses as it does historical periods. At the extremes of this range the largest of these targets should prove easy to identify, whereas the smallest would only be detected by the highest resolution of magnetic surveys. However, a survey designed to resolve anomalies of between five hundred and three thousand kilograms (0.5 – 3 tonnes) can be expected to identify archaeological material such as ships guns, anchors and concreted amalgamations of fastenings and fittings.

	Target Type							
	Small fe fasting	Large fe fastening	Large Round Shot	Medium Anchor	12lb Gun	32lb Gun	Large Anchor	Small steel wreck
Typical Mass (kg)	0.1	>10	15	700	1,200	2,800	4,000	<10,000

Fig 9 Typical archaeological targets and their mass

3.5.2 Magnetic anomalies

3.5.2.1 Hall's equation

The most commonly cited quantitative evaluation for marine magnetic data was published by Hall (1966):

$$\Delta M = 10^4 \frac{a}{b} \frac{w}{d^3},$$

where ΔM is the magnetic anomaly in nT, a/b is the length-to-width aspect ratio of the target, w is its weight in grams and d is the altitude of the sensor above the target in cm. The relationship was formulated in the days of cgs units when equations were often provided with pre-described units for its variables. However, this is not considered good practice any more and leads to confusion when different units are used. For example w/d^3 is sometimes replaced with W/D^3 where W is the weight in tonnes and D is the sensor altitude in metres, and Green (2003, 63) uses the equation with a factor of 10 instead of 10^4 and tries to compensate by requiring the altitude d to be in millimetres – this is wrong; it would have to be in deci-metres (1 dm = 0.1 m)! If one wants to use this equation without such confusion it should hence be written as

$$\Delta M = 10\,\mathrm{nT}\frac{\mathrm{m}^3}{\mathrm{kg}} \cdot \frac{a}{b} \frac{w}{d^3}$$

where all quantities have to be entered with their respective units and the final result is calculated taking all units into account. If the weight is entered in kilogrammes and the altitude in metres then the resulting magnetic anomaly will be in nanoteslas. This equation will henceforth be referred to as 'Hall's equation'.

Hall's equation is a particular version of a dipole approximation and its compatibility with theoretical models shall be examined in the following sections.

3.5.2.2 Omni-directional dipole approximation

A bar magnet or a compass needle are usually considered to be magnetic bipoles, having north- and south poles separated by a distance L and with a magnetic moment of strength m. The magnetic flux density B created by such bipoles can be calculated at the measurement distance d from the bipole (see below). However, if the measurement distance is much larger than the extent of the bipole (ie when the magnetic target looks tiny from the measurement position), a dipole approximation can be used. In addition, if all angular dependencies are neglected and the result for the direction perpendicular to the magnetisation is taken as an omni-directional approximation, the resulting expression is

$$B = \mu_0 \frac{m}{d^3},$$

where μ_0 is the magnetic permeability of free space ($4\pi \times 10^{-7}$ T m A^{-1}). This means that the magnetic flux density decreases with the third power of the distance between sensor and target, irrespective of the direction between them. The magnetic moment is often created by the induced magnetisation M of the target's material in the earth's magnetic field B_e with a strength determined by its volume specific magnetic susceptibility κ

$$m = M \cdot V = \kappa \frac{B_e}{\mu_0} \cdot V ,$$

where V is the volume of the magnetised sample. Hence the approximated omni-directional magnetic dipole anomaly is

$$B = \kappa \cdot B_e \frac{V}{d^3} .$$

This can also be expressed in terms of the sample's mass w using the bulk density $\rho = w/V$

$$B = \frac{\kappa}{\rho} B_e \frac{w}{d^3} = \chi \cdot B_e \frac{w}{d^3},$$

where χ is the mass specific magnetic susceptibility. This relationship has the form

$B = k \frac{w}{d^3}$ with

$$k = k_D = \frac{\kappa}{\rho} B_e = \chi \cdot B_e$$

where k_D is the numerical constant of this omni-directional dipole approximation.

Clearly, Hall's equation is also a form of the omni-directional dipole approximation for which he had chosen the parameter

$$k = k_H = \alpha \cdot k_{H1},$$

with the Hall Parameter k_{H1}=10 nT m^3/kg and the aspect ratio $\alpha = a/b$. This expression does not allow for variations in material properties but assumes that all targets are made of the same material and only their elongation (i.e. the aspect ratio) leads to variations in the measured flux density.

The omni-directional dipole approximation shall henceforth simply be referred to as 'dipole approximation'.

3.5.2.3 Parameters of the dipole approximation

The following numerical examples shall illustrate the estimates that can be derived by these relationships. Magnetic susceptibility of ferrous materials can vary widely, depending on the purity of the material involved (see Figure 10).

Material	κ (SI)
Ferrite U 60	7
Ferrite M33	750
Nickel (99% pure)	600
Ferrite N41	3,000
Iron (99.8% pure)	5,000
Ferrite T38	10,000
Silicon GO steel	40,000
supermalloy	1,000,000

Fig 10 Volume specific magnetic susceptibility of ferrous materials (after Clarke 2008)

With a magnetic susceptibility of pure iron (5000 (SI)) and a typical bulk density for iron of 7.9 g/cm^3 the mass specific magnetic susceptibility is χ = 633 × 10^{-3} m^3/kg. For comparison, the value for the iron-oxide magnetite is 0.6 × 10^{-3} kg/m^3. Combined with the magnetic flux density of the earth's magnetic field in northern Europe of ca 48,000 nT this would result in a constant of k_D = 30,770 nT m^3/kg, ca 3000 times larger than Hall's Parameter.

If, on the other hand, one were to convert Hall's Parameter into a mass specific magnetic susceptibility (ie $k_H = k_D$) the resulting value would be χ = 0.21 × 10^{-3} m^3/kg for an aspect ratio of 1:1. Using the bulk density of iron, the corresponding volume specific magnetic susceptibility would be κ = 1.65 (SI). Such value lies within the range for ferromagnetic steel (κ = 0.4 to 13 (SI) (Stainless Steel Advisory Service 2000). Values for these parameters, derived from measurements over known targets will be discussed below.

The mass used in the dipole approximation is of course the mass of the magnetic material in the target, for example the mass of an anchor. However, the 'weight' of a ship is not always quoted as its mass, but instead as the 'displacement', which is the amount of water the hull displaces (this is further complicated by the use of different definitions for a 'displacement ton'). In order to float, a ship's mass has to be less than its displacement. Therefore, using the displacement of a ship instead of its mass overestimates the magnetic anomaly caused.

To describe the geometry of the target through its aspect ratio $\alpha = a / b$ one has to make assumptions about its third dimension, the height, for example by assuming a square cross section (ie the height being the same as the width b). In this case the volume is given by

$V = a \cdot b^2 = \alpha b \cdot b^2 = \alpha \cdot b^3$, resulting in $b = (V / \alpha)^{1/3}$, hence

$a = \alpha \cdot (V / \alpha)^{1/3} = \alpha^{2/3} \cdot V^{1/3}$.

This shows that for a given volume (or mass) of a target, the length increases sub-linearly (ie with a power of 0.67) with the aspect ratio. How this influences the strength of the anomaly has to be investigated. That the anomaly strength should be proportional to the aspect ratio, as postulated by Hall ($k_H = \alpha \cdot k_{H1}$), is not directly obvious.

3.5.2.4 Bipole model

As stated before, the magnetic dipole approximation is only valid for large distances. Where the extent of the target cannot be neglected compared to the measurement distance the magnetic anomaly has to be calculated from a bipole model (Aspinall *et al* 2008, Chapter 3). To express the magnetic flux density created in its vicinity in a reasonably simple way it is useful to introduce polar rather than Cartesian co-ordinates. The magnetic flux density is then described in terms of its radial component B_r and the perpendicular angular (tangential) component B_θ. Each measurement position can be characterised by its distance r to the bipole's centre and the angle θ between this direction and the alignment of the bipole. Based on the orientation of the bipole and the dip of its axis with regards to the horizontal, these radial vector components can then be converted into Cartesian co-ordinates. As the maximum and minimum of the anomaly are aligned with the axis of the bipole it is convenient to align the x-axis of the Cartesian co-ordinate system with the axis of the bipole. The z-axis is considered to point upwards. The influence of the deviation of the x-axis from magnetic north on the results will be discussed below. The exact calculation of the components of the resulting flux density vector is elaborate and will not be detailed here.

3.5.2.5 Direction of magnetisation

Targets which are permanently magnetic, like a compass needle, are said to have a *remanent* magnetisation. This remanent magnetisation is fixed to the target and the magnetic flux density created by it remains aligned with the target, whatever its orientation. For example a brick that was fired to a high temperature (above *c* 600°C, its Curie temperature) in the earth's magnetic field will fix this magnetisation to its crystal structure (Schmidt 2007) and it will be strong and orientated in a defined direction. In contrast, had the brick not been fired, the clay of the brick would simply gain a much weaker *induced* magnetisation (determined by the clay's magnetic susceptibility κ) in the earth's magnetic field and this magnetisation would be aligned with the current direction of the earth's magnetic field (in fact, if the earth's field were to ceases, so would the induced magnetisation).

However, for solid targets with high magnetic susceptibility (*c* κ > 0.1 (Telford *et al* 1990) and an elongated shape (eg a canon) this is no longer true. In this case internal demagnetisation effects lead to a magnetisation vector that is always aligned with the long axis of the target and not with N-S. Hence even the induced magnetisation of such targets will be aligned with the target itself, irrespective of its orientation, and not along N-S. This is similar to the behaviour of remanent magnetisation but has a very different underlying cause. Many ferrous pieces that have disintegrated from shipwrecks can be described in this way, for example canons, guns or even pieces of steel cables. It was hence found that the orientation of the positive and negative magnetic peaks created by 'debris' on the sea floor is not influenced by the magnetic N-S direction but is aligned with the target's long axis. Enright *et al* report (2006, 136) that "[t]he average variation of debris anomalies from magnetic north in the sample (n = 17) is 66.4 degrees".

Targets with moderately high magnetic susceptibility but which do not form a clearly elongated and solid object, like the collapsed hulls of ships, exhibit a behaviour somewhere between the two extremes (ie not exactly aligned with the earth's magnetic field but also not aligned with the long axis of the target). So if the target is not 'dense' but 'empty', the magnetic anomaly 'tries' to align itself with the long axis but if the deviation from N-S becomes too great (and hence the forces pulling the magnetisation) the direction may flip to align with one of the shorter axes. As a result the magnetisation is aligned within ±45° of magnetic North. This is clearly visible in the examples presented by Enright *et al* (2006) where the lines connecting the major positive and negative parts of the anomalies are either aligned with the length of the hull or perpendicular to it. They report (Enright *et al* 2006, 136) that "all of the shipwreck anomalies … have declinations that vary less than 31 degrees from magnetic north", which fits well with the predicted ±45°. They illustrate one example where the alignment of the magnetisation is E-W, as the hull (Enright *et al* 2006, 23, Site 325), but dismiss this as being caused by a ferrous pipeline running 25 west of the bow. It is entirely possible that the alignment of the anomaly with the hull is not an artefact caused by the pipeline (which has an anomaly strength only 10% of the one created by the ship) but is a true alignment effect due to the high magnetic susceptibility and solid elongated shape of the boat. The wreck has been described as a steel-hulled vessel with dimensions 18–20 m × 5–6 m (Enright *et al* 2006, 22).

Since in any of these cases the measured anomalies are caused by features magnetised along either of their magnetic axes, they are best described by a bipole with the same orientation and dip as the target's axis.

3.5.2.6 Total field

The magnetic anomaly of the flux density B produced by a target's magnetisation outside of its body is superimposed on that of the earth's magnetic field so that a magnetometer measures a total flux density

$$\vec{B}^{tot} = \vec{B}^{earth} + \vec{B}$$

where the flux densities are added vectorially. This is the magnetic flux density measured by a magnetometer. If only one component of the flux density is measured by the magnetometer (e.g. using a fluxgate sensor to record the vertical component, as is often done in terrestrial surveys) the presence of the earth's magnetic field is simply an offset that can easily be subtracted from the measurement

$$B_z = B^{tot}{}_z - B^{earth}{}_z \,.$$

However, if an intensity measuring magnetometer is used (often called 'Total Field Magnetometer' (Aspinall *et al* 2008, Chapter 2)) the relationship is more complicated since, in general,

$$\left|\vec{B}\right| \neq \left|\vec{B}^{tot}\right| - \left|\vec{B}^{earth}\right|$$

The reason is that vectors that point in different directions may partly cancel each other out and the intensity of the resulting vector is not the sum of the original intensities. Therefore these measurements are usually expressed as Total Field Anomalies F by subtracting a background value of the earth's magnetic field from the measured total intensity

$$F = \left|\vec{B}^{tot}\right| - \left|\vec{B}^{earth}\right|.$$

It is very important to realise that this Total Field Anomaly is different from the intensity of the anomaly vector (Schmidt and Clark 2006). Since the earth's magnetic field (ca. 48,000 nT in northern Europe) is considerably stronger than the typically encountered magnetic anomalies (eg 1,000 nT) it can be shown (Blakely 1996) that the Total Field Anomaly can be calculated as the component of the anomaly vector that points in the direction of the earth's magnetic field.

This has two important implications. First, the exact shape of the Total Field Anomaly depends on the magnetic latitude of the measurement. At the magnetic pole, $F = B_z$, whereas at the magnetic equator $F = B_{North}$. Hence an intensity sensing magnetometer measures just one component of the magnetic anomaly (similar to a vector magnetometer), but which component this is depends on the measurement location. Second, the horizontal angle between the anomaly vector and the earth's magnetic field (the strike angle, see Figure 11) also influences the Total Field Anomaly. As the strike angle increases the contribution of the vector anomaly's horizontal component B_H to the Total Field Anomaly decreases with the cosine of the strike angle. This means that at a strike angle of 90° (ie E-W) the horizontal component does not contribute to the Total Field Anomaly which then has the same shape as the vertical component B_z albeit at lower amplitude as it is only the projection of the vertical component into the direction of the earth's magnetic field that contributes.

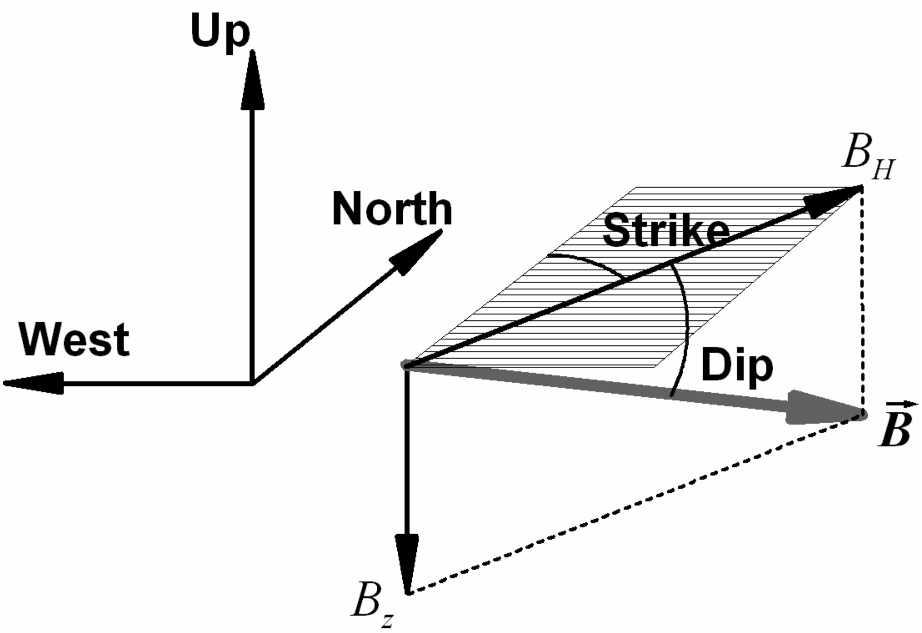

Fig 11 Angles of the vector anomaly $\vec{B}$

3.5.2.7 Modelling of bipole anomalies

The mathematical relationships described in the previous sections were implemented in a spreadsheet to calculate the Total Field Anomaly of a bipole as a magnetometer traverses directly over the target on a path aligned with the target's axis. It is on this path that the highest positive and lowest negative readings are encountered. In accordance with aerial and terrestrial magnetic surveys the calculated strength of the anomaly was taken as the positive maximum peak height of the anomaly ('peak height'). In marine magnetic surveys it is common practice to take the total difference between the positive and negative part of an anomaly's trace (ie its 'total amplitude') as the strength of response. The implications of this will be discussed below.

The size of the target is derived from its mass, the aspect ratio and a given bulk density. Changing the mass hence alters the magnetisation and also the dimensions of the target. Two models were used as reference for the variation of parameters. The 'dense' model has the bulk density of iron and represents compact targets, like canons or canon balls. The 'empty' model represents a mainly empty target with a bulk density lower than that of water (taken as 10% of iron's bulk density), as would be required for a ship to float. A ship's hull would hence show similar properties to this model. For both models the volume specific magnetic susceptibility was chosen such that the mass specific magnetic susceptibility corresponds to Hall's Parameter (χ = 0.19 × 10^{-3} m^3/kg, see above). Other values would simply scale the overall amplitudes and would not change any relationships derived from the shape of the anomaly.

		Dense	***Empty***
volume specific magnetic susceptibility	κ	1.65 (SI)	0.165 (SI)
bulk density	ρ	7.9 g/cm³	0.79 g/cm³
earth's magnetic field	B_e	48,000 nT	
inclination of earth's field		68°	
target's mass	w	1,000 kg	
aspect ratio	α	1	
altitude of magnetometer over top part of target	d	6 m	
dip of target		0°	
strike of target		0°	
derived length of target		0.50 m	1.08 m
anomaly strength (dipole approximation)		46.4 nT	46.4 nT
peak height (bipole model)		33.5 nT	33.3 nT
total amplitude (bipole model)		77.1 nT	76.6 nT

Fig 12 Parameters for reference models for bipole anomaly

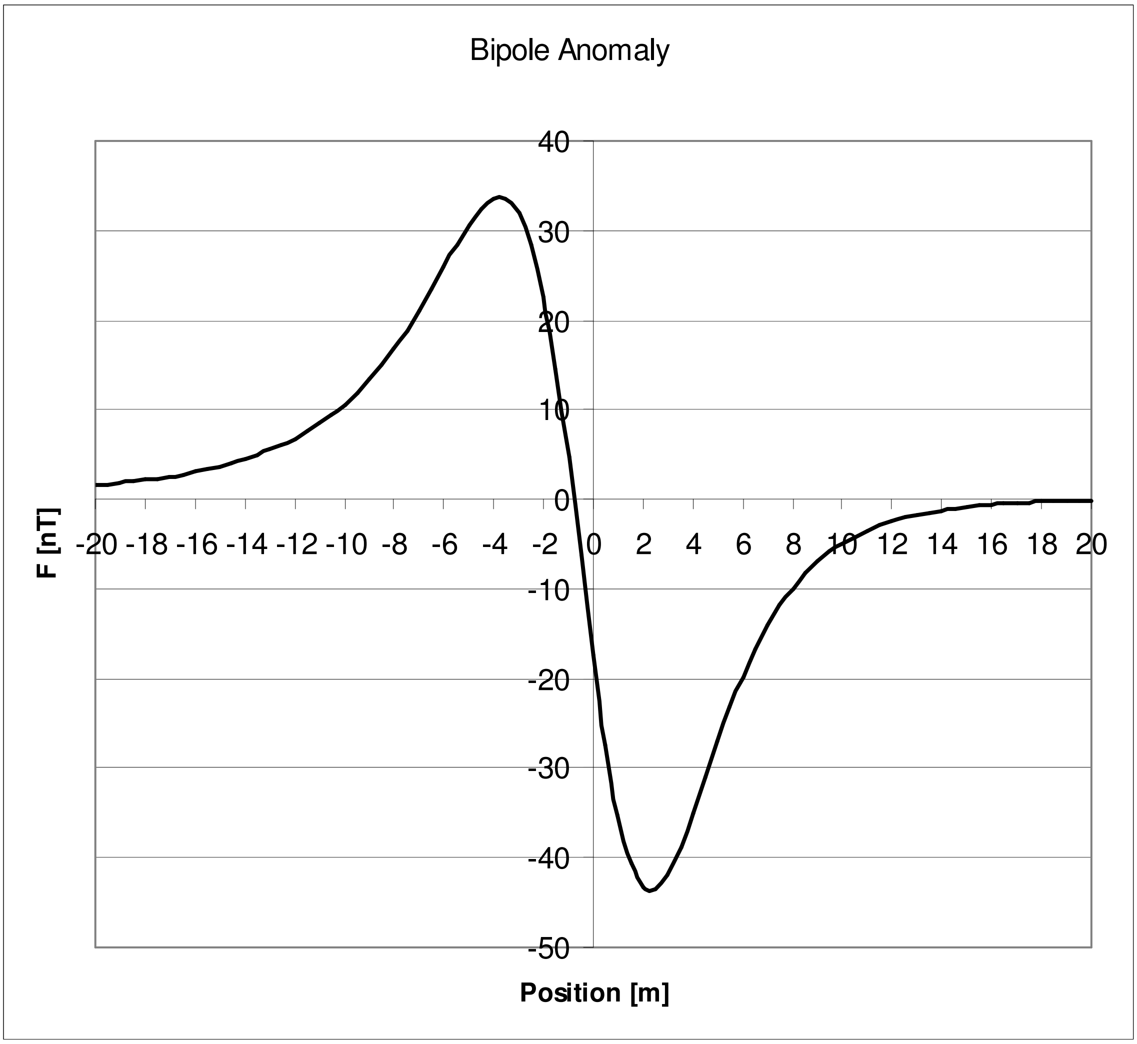

Fig 13 Bipole anomaly for the dense reference model (Figure 13) passing from south to north (left to right) with the centre of the target at position 0 m

The altitude of the magnetometer over the targets was chosen as 6m in accordance with the recommendations by Dix *et al* (2008, 59). As many elongated targets lie horizontally on the seabed, a dip of 0° was selected for the reference models. All subsequent Total Field Anomaly values are presented relative to the anomaly strength calculated for the bipole model of these parameters. Figure 13 shows the anomaly for the dense model. The empty model has virtually the same trace; the maximum deviation between them is 0.4 nT.

3.5.2.8 Altitude

When varying the altitude of the magnetometer over the target from 1m to 27m the anomaly amplitude of the dense model decreases with a power of 2.96, very close to the theoretical dipole value of 3. This can be seen in the linear trend of the double-logarithmic plot in Figure 14. For the empty model with approximately double the length, the decrease is with a power of 2.93.

As the altitude of the measurement sensor over the dipole increases the anomaly becomes wider. This is measured as the Full Width at Half Maximum (FWHM) of the positive peak (Figure 15). The dependency is linear in the investigated range of 1-15 m but the linear fit has a slope of 1.0593. Hence the FWHM is slightly wider than the altitude of the sensor over the target. However, this is clearly a very good approximation for the altitude!

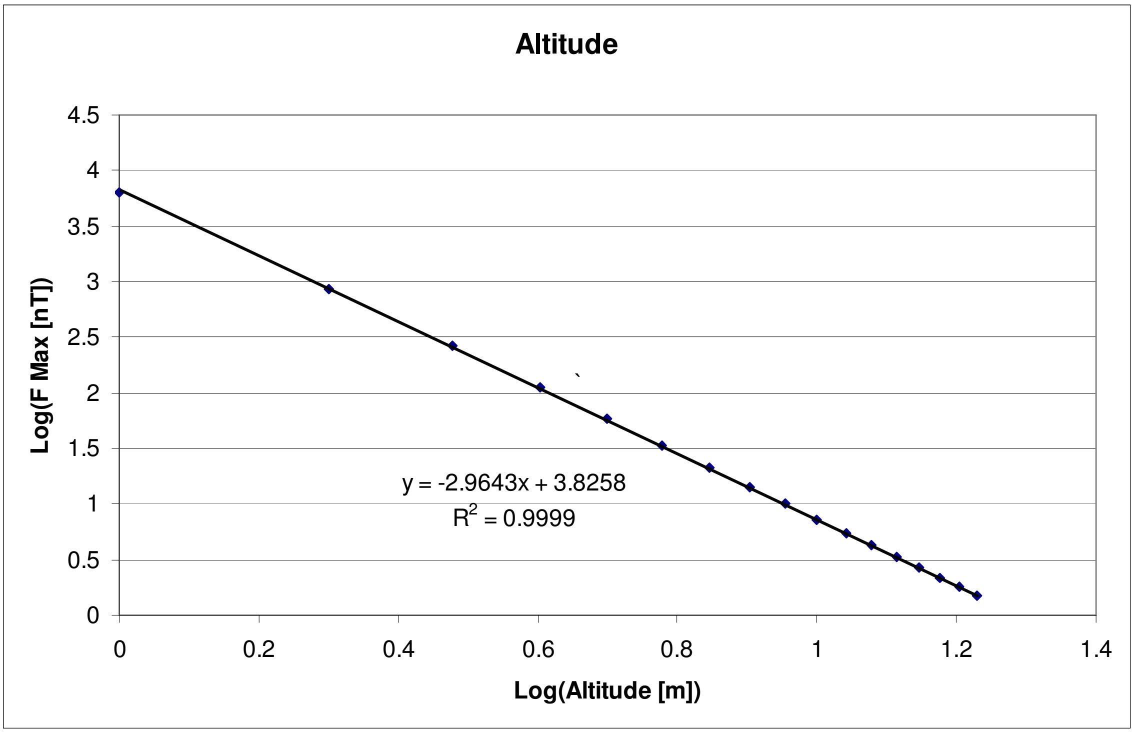

Fig 14 Double logarithmic plot of the decrease of the peak height with increasing altitude for the dense model. The slope of -2.96 is very close to the value of -3 for a dipole approximation

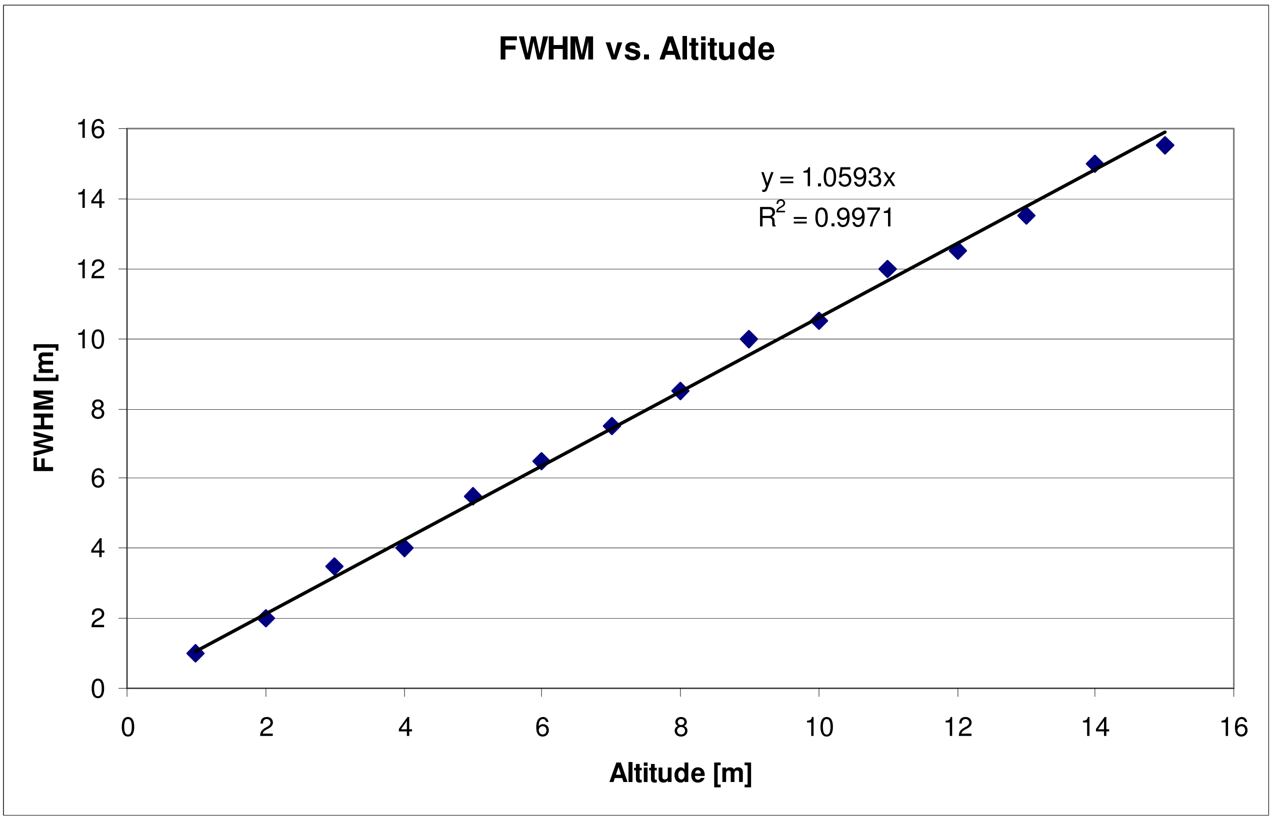

Fig 15 Change of the positive peak's width with altitude. The width is measured at half the peak height (Full Width at Half Maximum). The linear dependency has a slope slightly larger than 1

3.5.2.9 Mass

Varying the mass from 500kg to 500 tonnes changed the size of the dense target from 0.40m to 3.99m and of the empty target from 0.86m to 8.58m (ie longer than the investigation altitude of 6 m). The increase in mass led to a proportional increase of the magnetic moment ($m = M \cdot V = \kappa \cdot B_e \cdot V / \mu_0 = \chi \cdot B_e \cdot w / \mu_0$) and to a longer length of the bipole. For smaller mass (and shorter length) the peak height increases nearly proportionally with the weight as the spatial extent of the bipole has little influence. For longer targets there is a clear deviation from such proportionality (Figs 16 and 17) as the effect of the bipole becomes more pronounced.

Model	*Maximum length of target used for fit*	*Maximum mass*	*Slope of proportional fit*	*Squared regression coefficient*
Dense	0.75 m	3.3 tonnes	0.9990	1.0000
Dense	2.33 m	100 tonnes	0.9765	1.0000
Dense	3.99 m	500 tonnes	0.9260	0.9995
Empty	8.58 m	500 tonnes	0.7434	0.9945

Fig 16 Proportional fit of peak height to mass of target

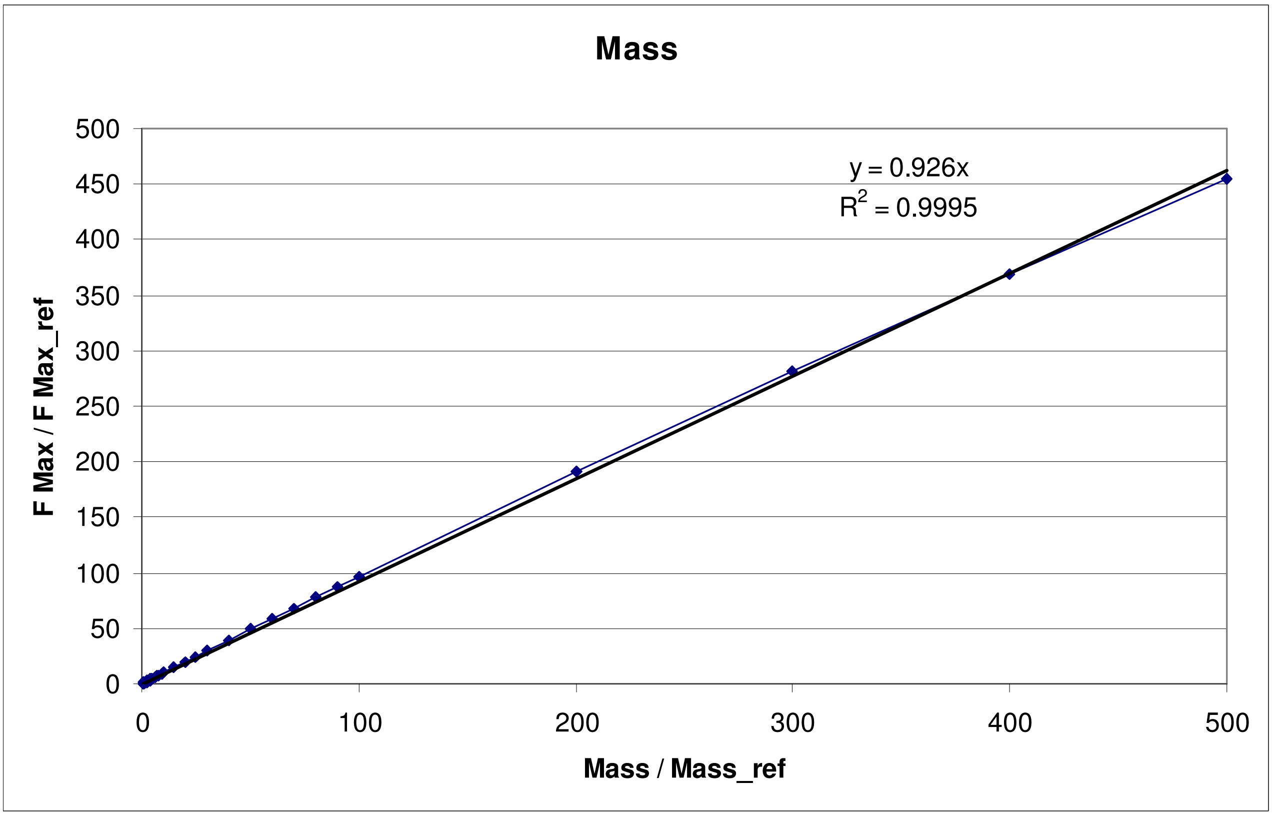

Fig 17 Nearly proportional increase of anomaly with mass for the dense model

3.5.2.10 Aspect ratio

Noteworthy is the dependency of the anomaly on the aspect ratio since this was introduced into Hall's equation as an additional parameter, not found in the dipole approximation. Varying the aspect ratio from 1:1 (ie the target is a cube) to 15:1, while maintaining a constant mass of 1,000kg changed the length of the dense target from 0.50m to 3.05m and the width from 0.50m to 0.20m. The empty target changed its length from 1.08m to 6.58m (ie somewhat longer than the altitude) and its width from 1.08m to 0.44m. The resulting variation of the anomaly has a slightly parabolic shape (Figure 19), but with a *decreasing* tendency. A target with larger aspect ratio hence has a smaller magnetic anomaly, in contrast to what is postulated in Hall's equation. The results of a linear fit that is forced through the point (1,1) are given in Figure 18 For greater lengths, as exhibited in the empty model, the linear fit is fairly good (Fig 20). The main difference is not between peak height and total amplitude but between short and long features.

Model	*Measure of anomaly*	*Slope of fit*	*Squared regression coefficient*
dense	peak height	-0.0041	0.9821
dense	total amplitude	-0.0044	0.9831
empty	peak height	-0.0142	0.9956
empty	total amplitude	-0.0162	0.9973

Fig 18 Linear fit of the anomaly strength to the aspect ratio

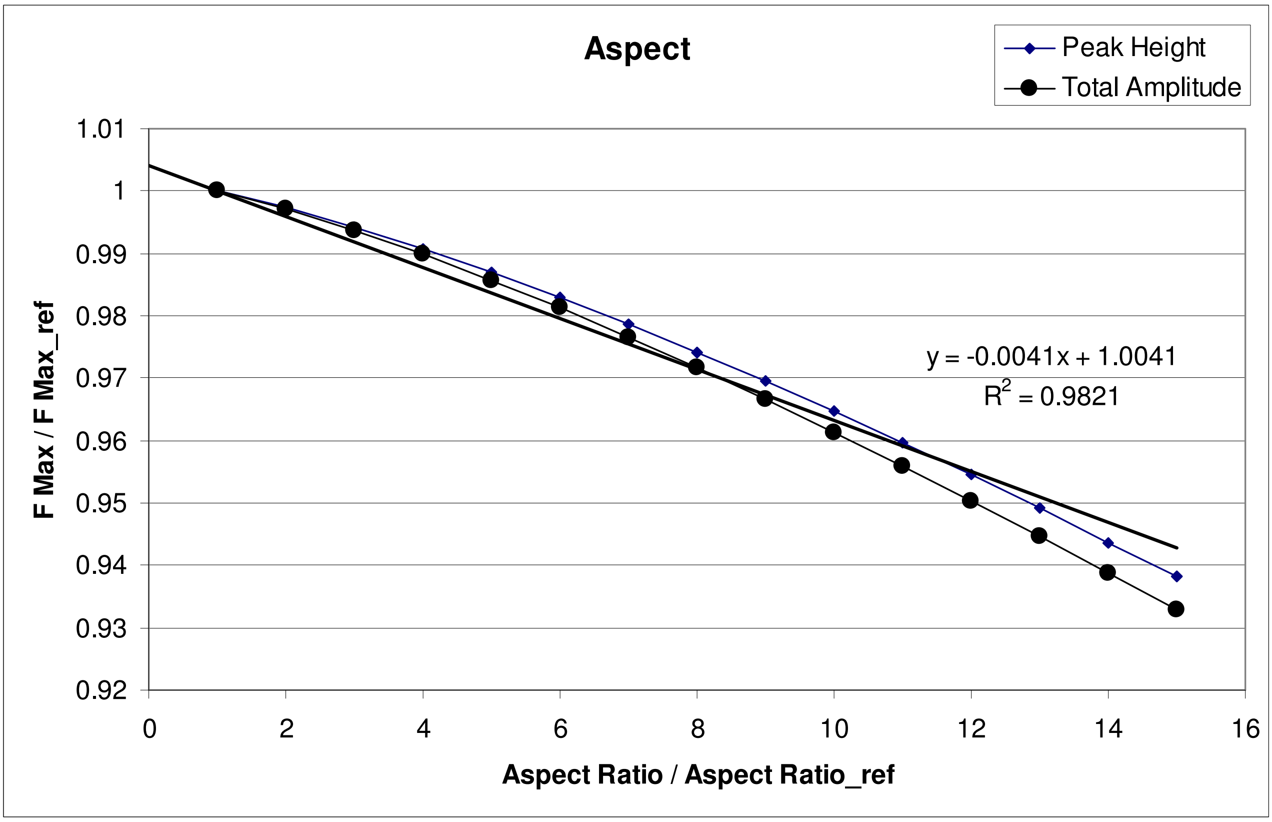

Fig 19 Decrease of anomaly with aspect ratio (ie elongation) for the dense model

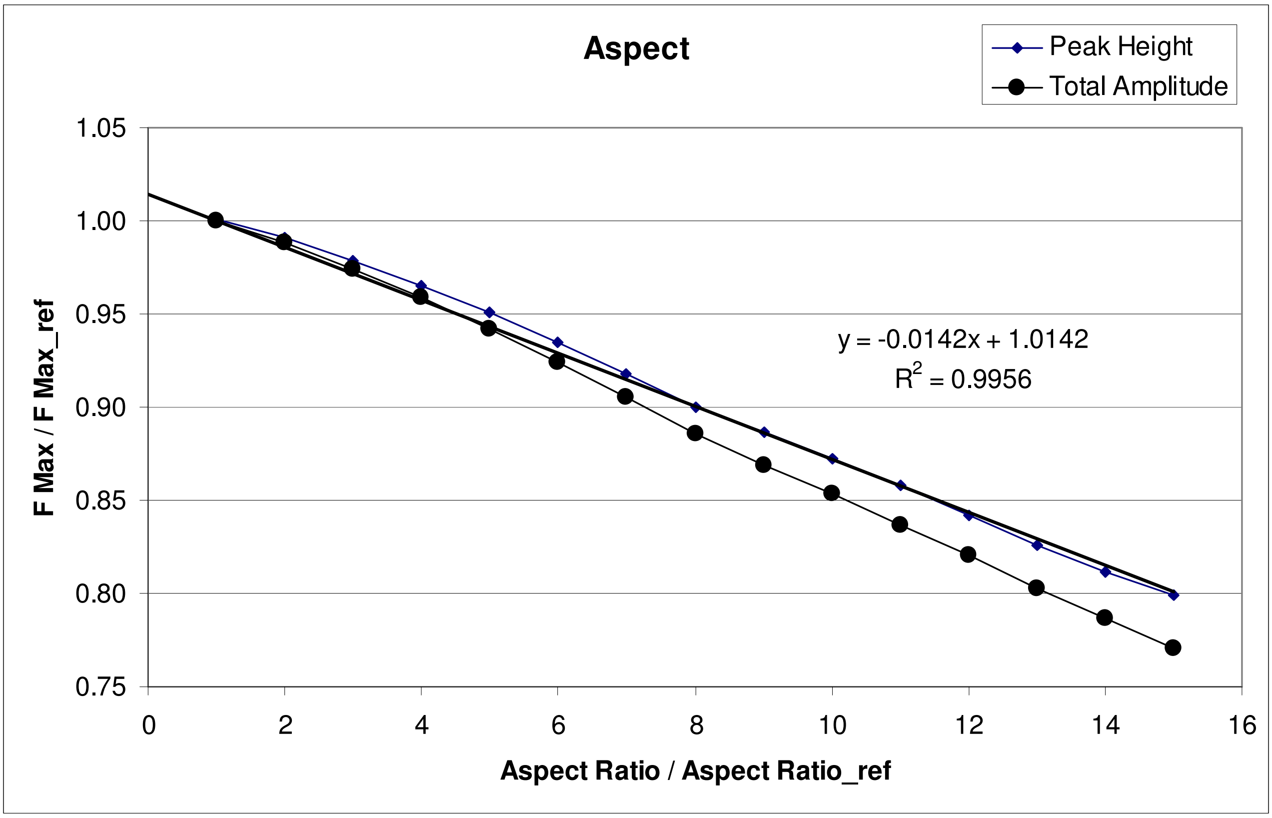

Fig 20 Decrease of anomaly with aspect ratio (ie elongation) for the empty model

3.5.2.11 Dip

As the target dips more steeply the positive maximum of the anomaly increases. This is due to the deeper end of the bipole contributing less to the anomaly as it sinks deeper (the modelling was such that the altitude over the 'upper end' of the bipole remained fixed and only the 'deeper end' was lowered). As the two ends have opposite magnetic effects (ie north- and south-pole) the cancellation effect of the 'deeper end' becomes weaker. The increase of the peak height is nearly perfectly linear in the sine of the dip angle (Fig 21). For the dense target the fitted slope is 1.3066, for the empty target it is 1.0624 (the fits were forced through (0,1)). This weaker dependency of the longer target on the dip is a consequence of the greater length of the empty target. The two poles do not cancel each other out as much in the first place and suppressing the second pole by lowering it does therefore not weaken the anomaly as much.

The shape of the anomaly changes considerably for steeper dips; Figure 22 shows the anomaly of the dense target for a dip of 70°. It clearly shows how the positive maximum dominates the shape of the anomaly and the negative minimum has become much weaker. It is hence important to consider the dependency of the total amplitude on the dip angle. This is shown as the second trace in Figure 22. The dependency on the dip angle is very weak demonstrating that the combined effect of the positive and negative poles, as represented by the total amplitude, remains nearly the same. Not only does the lowering of the negative pole weaken the positive peak less, but the remaining negative part of the anomaly also becomes smaller. The total amplitude hence remains virtually unchanged.

As a result, the amplitude ratio (peak height/total amplitude) forms a near linear relationship with the sine of the dip angle, as shown in Figure 23. For the dense model the relationship is amplitude ratio = 0.4957 sin(dip)+0.4498, the empty model shows only slightly different linear fit parameters (0.4955 sin(dip)+0.4509). It is hence possible to use this amplitude ratio for an estimate of the dip angle.

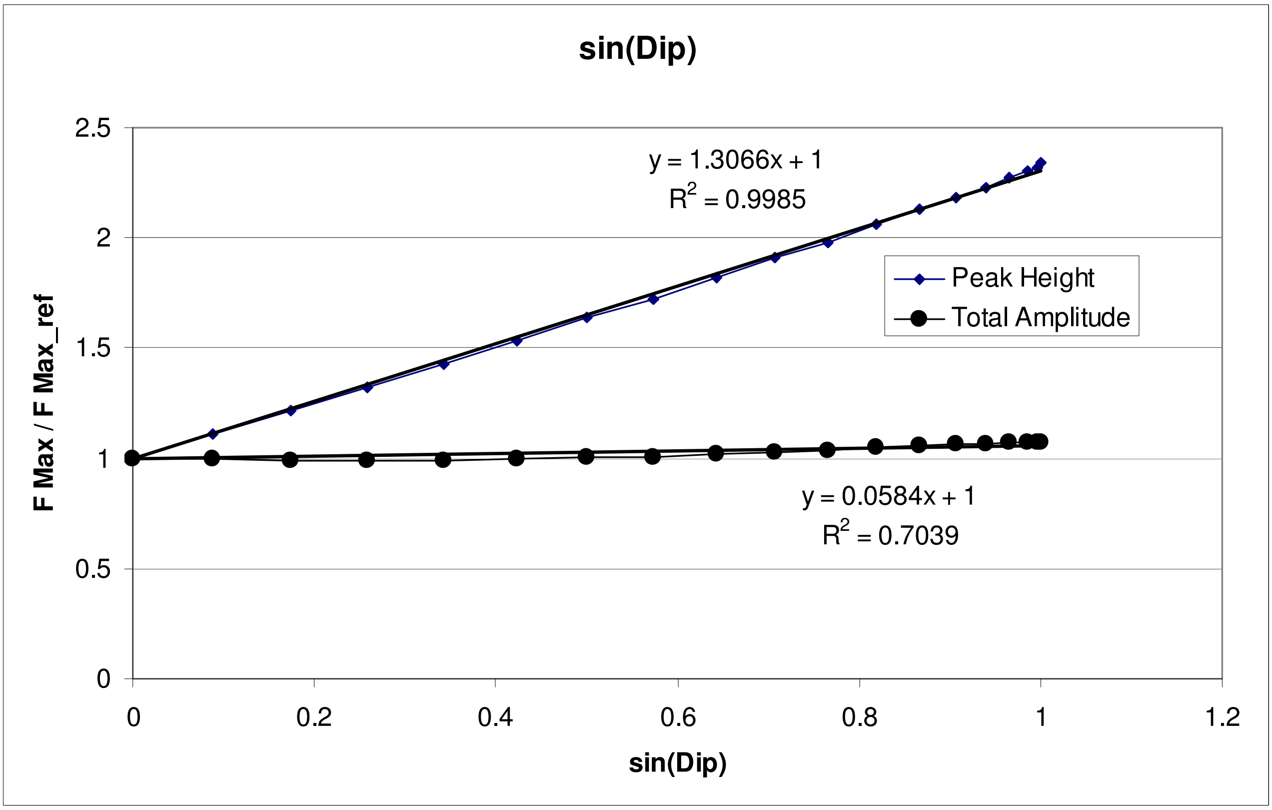

Fig 21 Increase of anomaly with dip for dense model

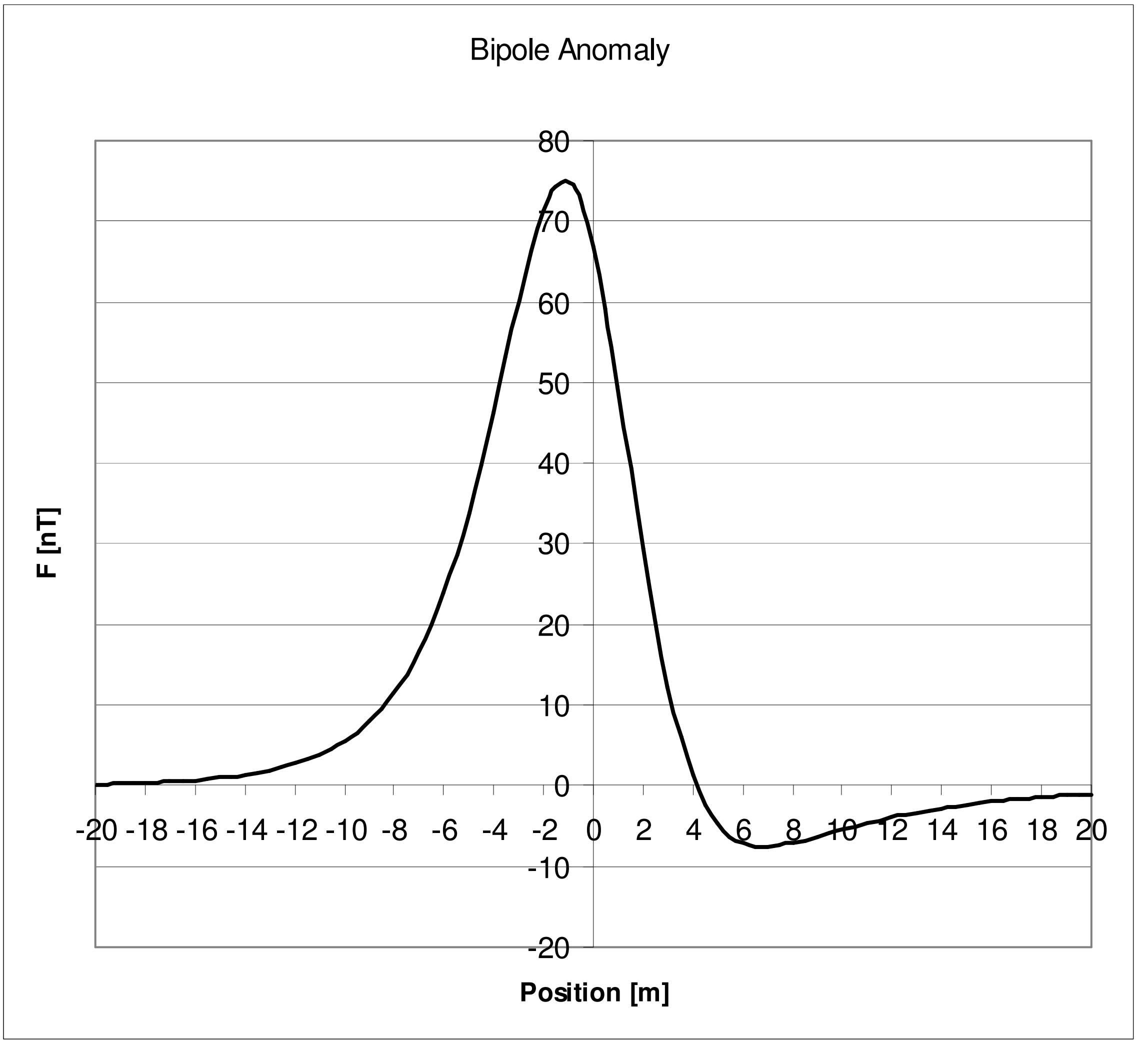

Fig 22 Bipole anomaly for a 70° dip angle of the dense model

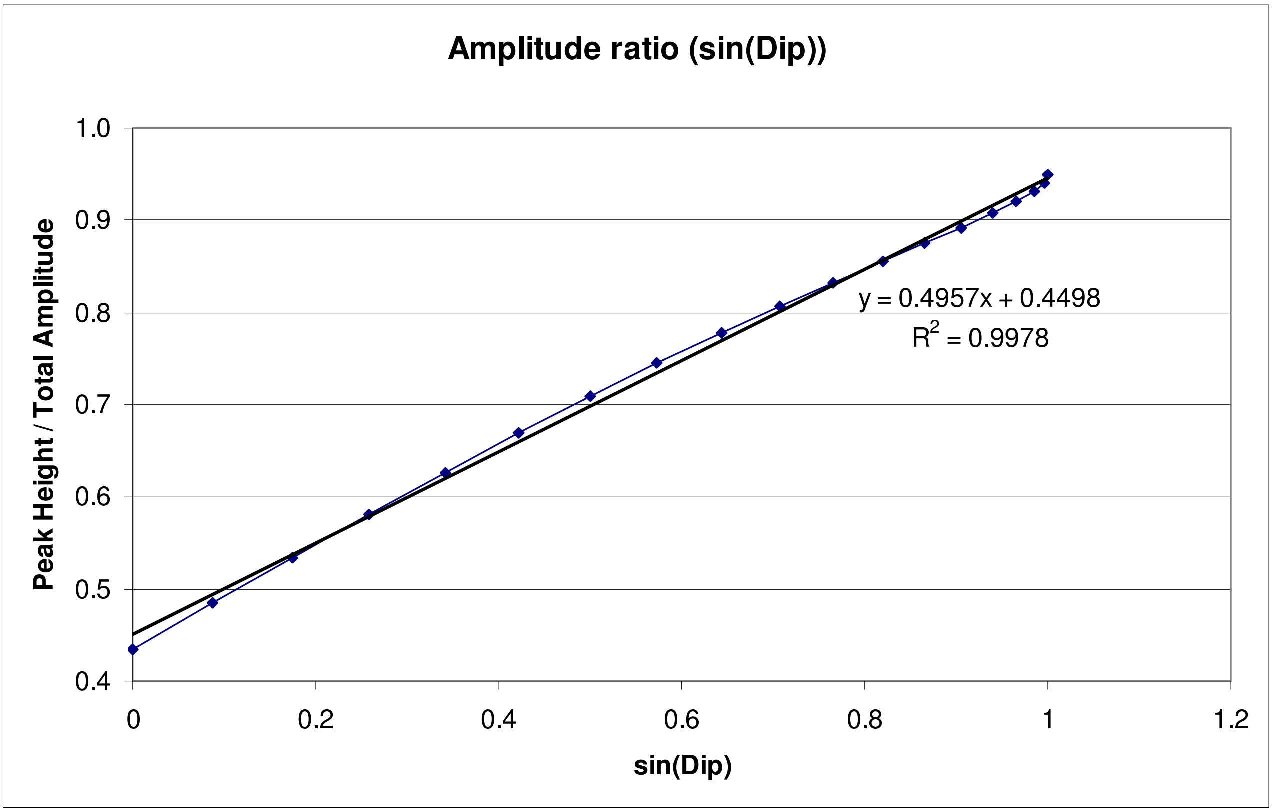

Fig 23 Change of the amplitude ratio in a bipole model with varying dip angles for the dense model

3.5.2.12 Strike

There is a weak increase of the anomaly with the strike angle (Figure 24) for the dense as well as for the empty model. As discussed above, the increasing strike angle leads to a decreased contribution of the anomaly vector's horizontal component. The observed increase of the peak height with the strike angle therefore shows that the horizontal component points west, not east over the maximum of the anomaly, since only then can it partly cancel the vertical component when projected onto the direction of the earth's magnetic field. This observation has little interpretational value.

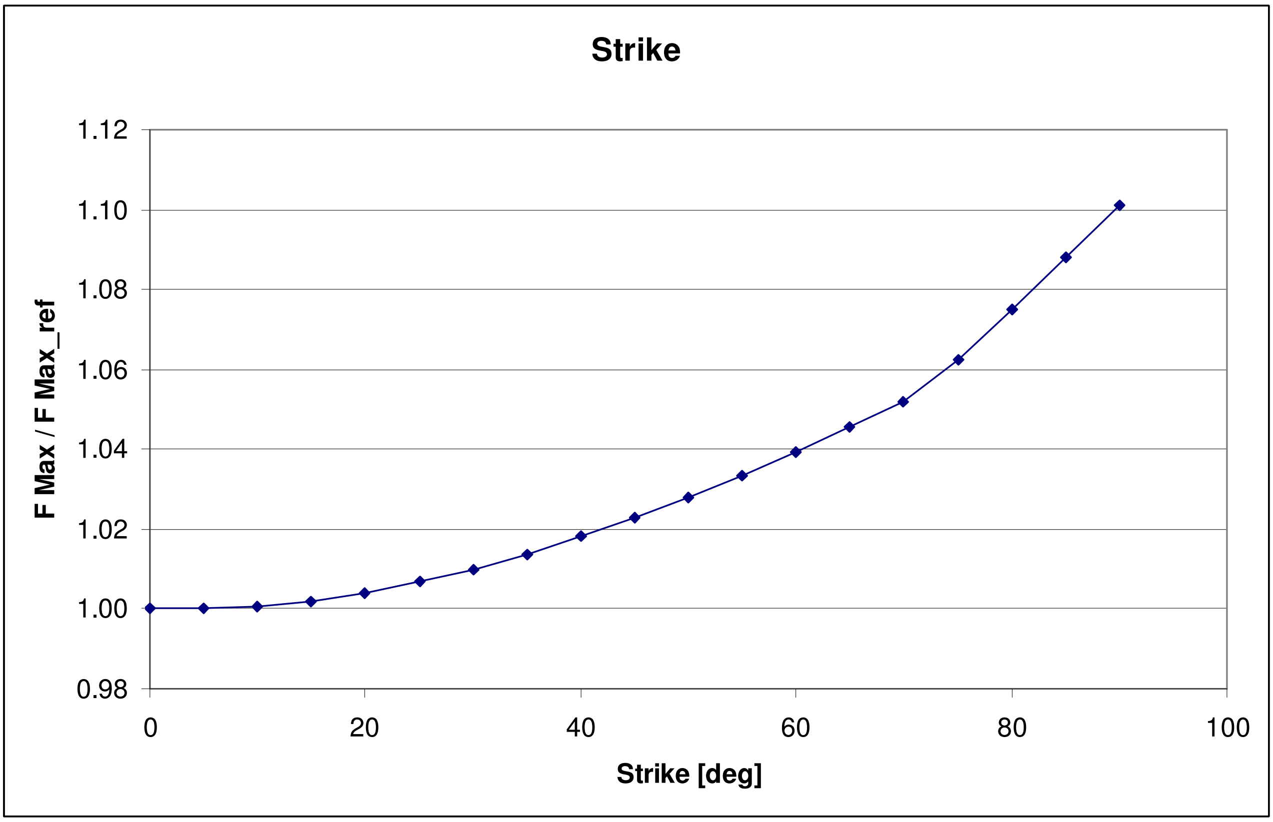

Fig 24 Increase of peak height with strike for dense model

3.5.2.13 Estimation

The strength of the calculated anomaly can be described either by the peak height or by the total amplitude. The dipole approximation's estimate is bigger than the former but smaller than the latter, as shown in Figures 25 and 26. Overestimation is the ratio of dipole approximation / bipole peak height, while underestimation is the ratio of dipole approximation / bipole total amplitude. As can be seen from the two figures, the overestimation of the peak height lies between 1.4 and 1.8 for the horizontal target (i.e. strong positive and negative parts) even when the target's length is extended via its aspect ratio. However, it drops from 1.4 to 0.6 (ie an underestimation) as the target dips down vertically. The underestimation of the total amplitude lies more consistently between 0.6 and 0.8, and is virtually unchanged for the dipping target. It is worth emphasizing that the increase of over- and underestimation with the aspect ratio (Figure 25) means that the actual anomaly strength *decreases* with the aspect ratio (see above).

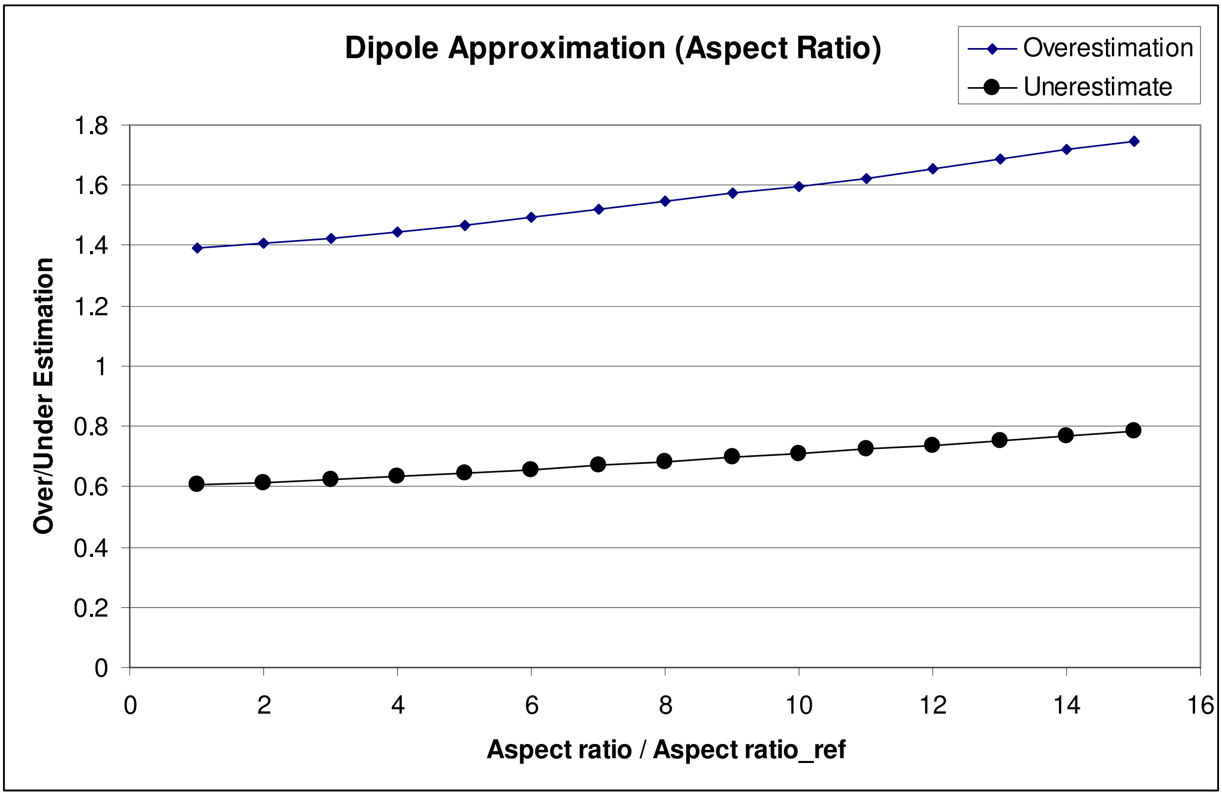

Fig 25 The dipole approximation overestimates the peak height and underestimates the total amplitude. Both show similar dependency on the aspect ratio for the empty model

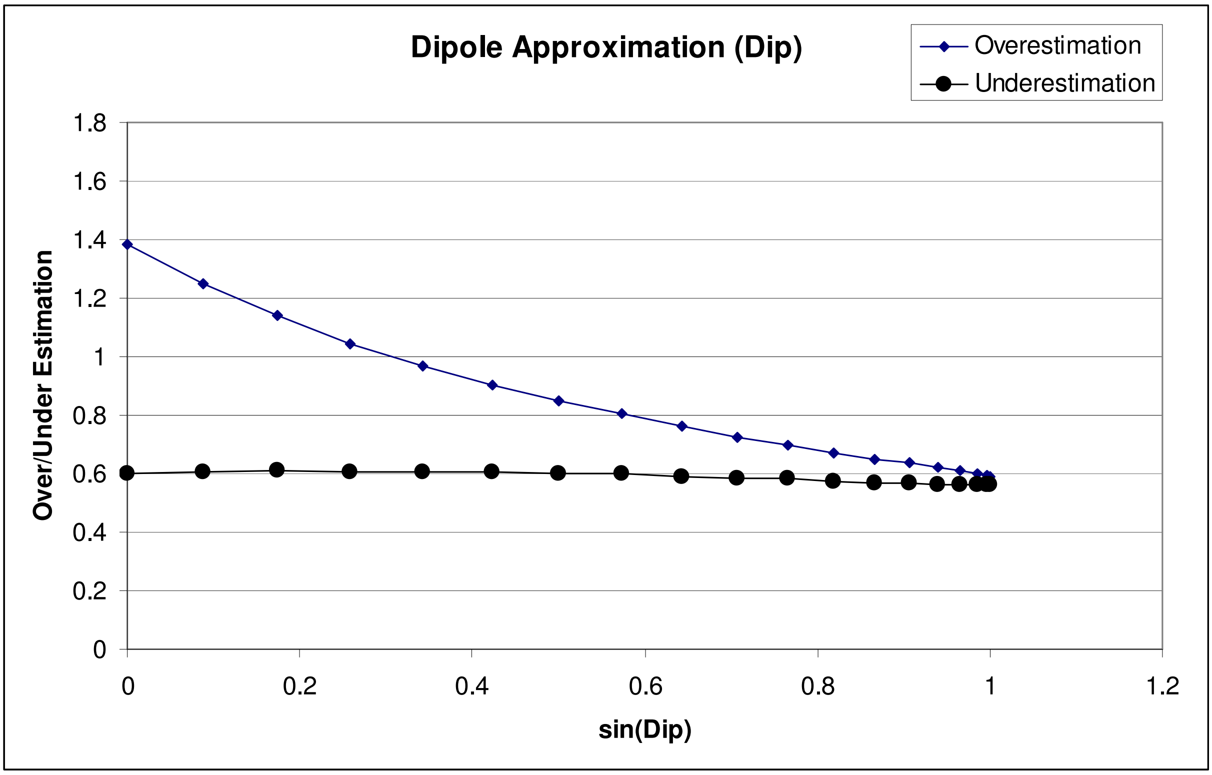

Fig 26 the dipole approximation over- and underestimates the peak height and underestimates the total amplitude. The dependency on the dip of the target (here for the dense model) is very different for the two estimates

3.5.2.14 Evaluation

Based on the variation of the various parameters in relation to the two chosen reference models several observations can be made.

Overall, the dipole approximation allows a fairly good prediction of the strength of the magnetic anomaly of the dipole model. Although the bipole calculations show that the actual extent of the target influences the anomaly, these changes are not huge for the range of parameters considered here.

- The dipole approximation predicts better the total amplitude of the magnetic anomaly (ie from positive maximum to negative minimum) than just the positive maximum peak, which is normally used for aerial and terrestrial data ('peak height'). In particular, the total amplitude shows considerably less dependency on the dip of the target. The dipole approximation only estimates 0.6-0.8 of the total amplitude (see Figure 26).
- The decrease of anomaly strength with altitude of the sensor over the target is close to an inverse third power law, with an exponent of 2.96 for the peak height. As expected, the relationship is almost identical to the dipole approximation for large distances, but for smaller distances the deviations are noticeable. For example, at an altitude of 6 m, the difference is 7%.
- The target's size is linked to its mass by way of bulk density and aspect ratio (α = length / width). However, as the mass of a target increases, its larger size only has little effect on the anomaly strength, which remains largely proportional to the target's mass. This increase is hence well described by the dipole approximation. It is important to use the mass of the magnetic components and not any other 'weight', like a ship's displacement.
- For a given mass of a target, its length increases with the aspect ratio which leads to a small decrease in the anomaly strength (both for the peak height and the total amplitude). This is in contrast to Hall's equation, which predicts a positive proportionality between the aspect ratio and the anomaly.
- The steeper a target dips; the larger will be the anomaly's positive peak. The total amplitude, however, is only weakly affected as the increase of the positive peak is compensated by a decrease of the negative trough. If instead of the target dipping, the measurement position were to rotate around the target, the same conclusion would apply. It is hence justifiable to use the omni-directional dipole approximation.
- The exact value of the anomaly strength crucially depends on the properties of the magnetic material in the target that creates the anomaly. These properties are often very difficult to evaluate and as a result the estimated anomaly strength can vary by a factor of up to 3000 (see above). In the light of such uncertainty, all small dependencies on other parameters appear negligible.
- Even for the bipole, the Full Width at Half Maximum (FWHM) is a good predictor for the altitude of the sensor above the target.

Therefore, the recommended relationship for estimating the magnetic anomaly caused by a marine magnetic target is

$$B_A = k_A \frac{w}{d^3},$$

where B_A is the total amplitude of the anomaly (from positive peak to negative trough) and k_A is the numerical constant for the adjusted dipole approximation.

$k_A = k_D \gamma / u$,

where

$k_D = \dfrac{\kappa}{\rho} B_e = \chi \cdot B_e$ is the numerical constant for the dipole approximation (see above),

$\gamma = 1 + 0.0162 \cdot (1 - \alpha)$ is the aspect depression that reflects the decrease of the anomaly with increasing aspect ratio and

$u = 0.6...0.8$ is the underestimation of the total amplitude by the dipole approximation.

[κ is the volume specific magnetic susceptibility, χ the mass specific susceptibility, ρ the bulk density, B_e the flux density of the earth's magnetic field (ca. 48,000 nT), w the mass of the target and d the altitude of the magnetometer above the target, aspect ratio α = length / width.]

The values for the mass specific magnetic susceptibility χ can vary, for example from 0.21 × 10^{-3} m^3/kg. (the value used in Hall's Parameter) to 633 × 10^{-3} m^3/kg (the value for pure iron). γ decreases from 1.00 to 0.85 as the aspect ratio increases from 1:1 to 10:1 and an average underestimation of 0.7 leads to an underestimation boost of $1/u =$ 1.43. However, considering the uncertainty about the parameters of actual material property (magnetic susceptibility and mass of magnetic material), the deviation of γ and u from 1 may be negligible.

This leaves to speculate why Hall included the aspect ratio as a proportionality constant in his equation (1966). This study has clearly shown that an elongated target, represented by a bipole, produces a slightly weaker anomaly, not a proportionally bigger one. It is possible that Hall wanted to express the fact that some elongated targets have a higher magnetic susceptibility, as it is the combined aspect ratio and magnetic susceptibility that enter Hall's equation ($k_H = \alpha \cdot k_{H1}$, see above). For example, a ship's hull (elongated) may have a more ferrous character than an anchor (length and width similar) made of some alloy. However, this is pure speculation and the considerations that lead Hall to his equation are unclear.

3.5.2.15 Lateral variation

Given that the altitude dependence of a bipole's anomaly is well described by an inverse-cube law and that the dip has little influence on the total amplitude, the omni-directional dipole approximation can be used to describe the change of the anomaly with the radial distance ('slant range') from a target. This is important if the measurement is not recorded directly above a target, but a lateral distance x to the side (Figure 27).

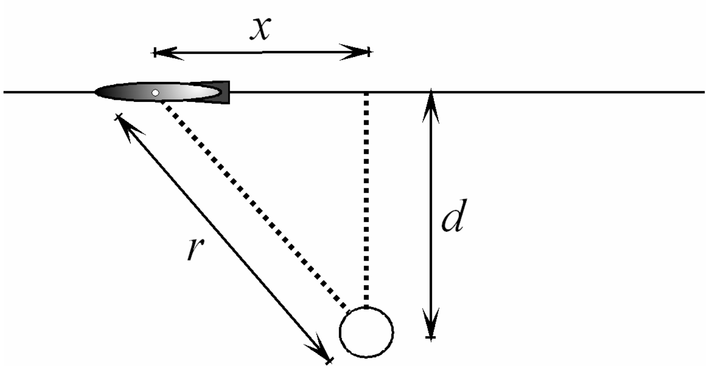

Fig 27 Lateral and radial distance to the target

The relationships then become

$B_A = k_A \frac{w}{r^3}$ with $r = \sqrt{x^2 + d^2}$, hence $B_A = k_A \frac{w}{(x^2 + d^2)^{3/2}}$.

The resulting traces for different altitudes above the target (Figure 27) are equivalent to those published by Green (2003, 73) using the mass specific magnetic susceptibility derived from Hall's equation for an aspect ratio of 5 (χ = 1.05 × 10^{-3} m^3/kg) and a mass of 10,000 tonnes.

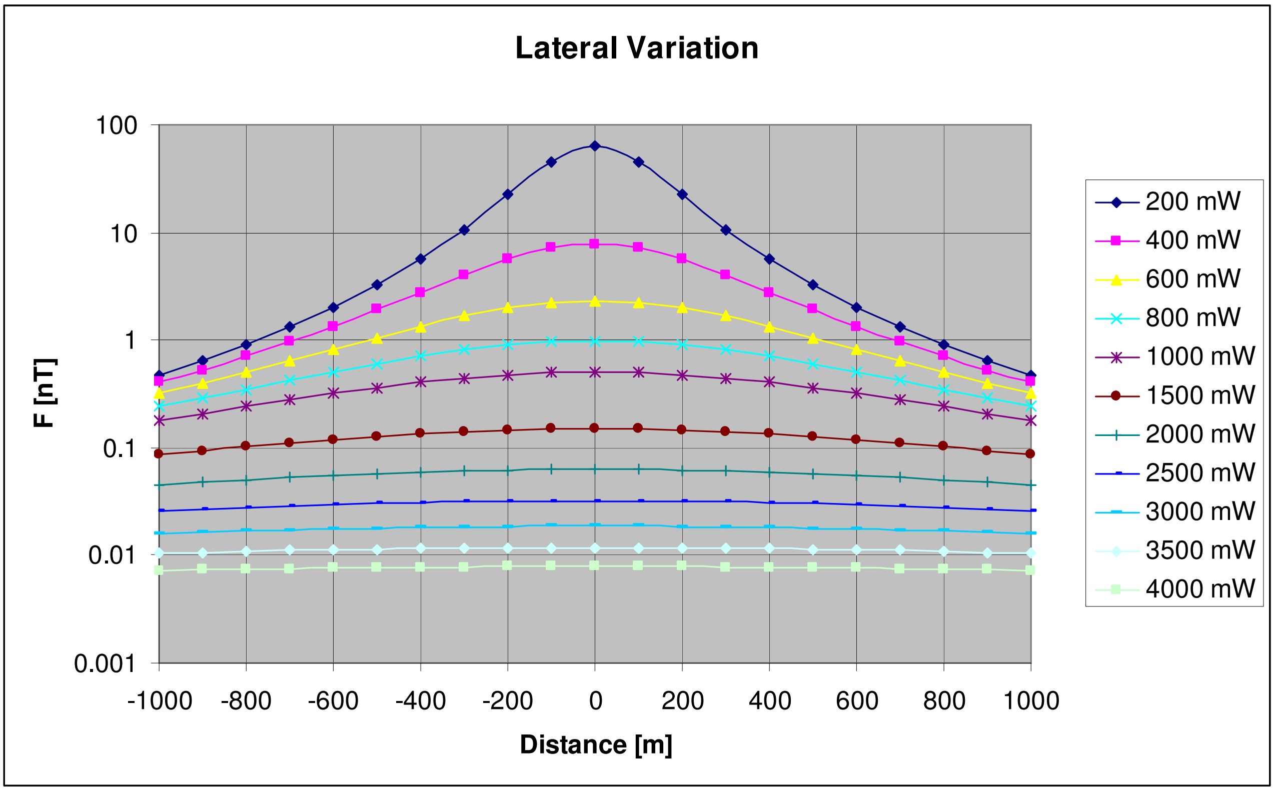

Fig 28 Change of estimated total amplitude with lateral distance from target for different depths

3.5.2.16 Between-track estimation

If the anomaly is measured on two adjacent tow-lines and the altitude of the measurement is known for each line (ie the height of the magnetometer above the sea floor) then the location of the target along the straight line connecting the two anomalies can be calculated by using the omni-directional dipole approximation. If the distance between the two measured anomalies is s, the two total amplitudes are B_{A1} and B_{A2}, and the altitudes of the sensor are d_1 and d_2 (Figure 29) then the distance of the target from the first recorded anomaly can be calculated as

$$x_1 = \left(\sqrt{s^2\beta^2 + \left(\left(s^2 + d_2{}^2 \right) \cdot \beta - d_1{}^2 \right) \cdot (1-\beta)} - s\beta \right) \Big/ (1-\beta) \text{ with } \beta = \left(\frac{B_{A2}}{B_{A1}} \right)^{2/3}.$$

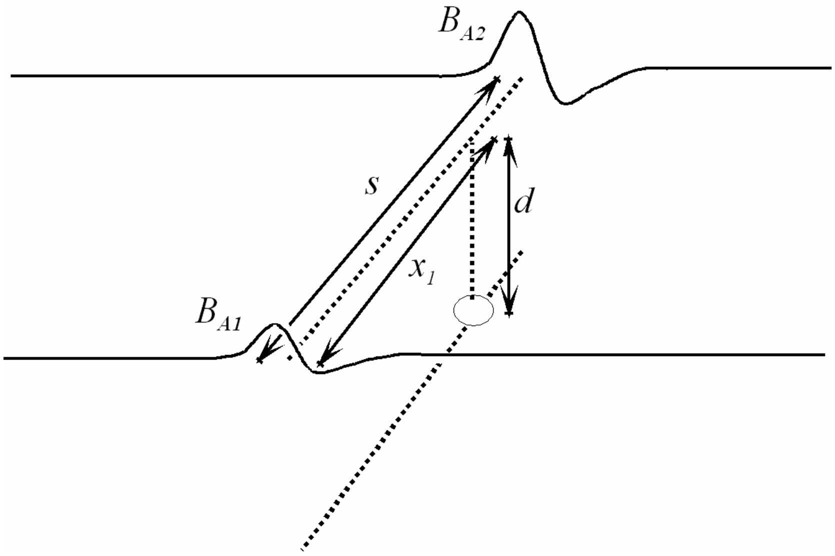

Fig 29 Anomalies on adjacent lines

For example, if the anomaly measured 10 nT on the first tow-line and 20 nT on the second tow-line, the direct distance between these two anomalies were 10 m and the magnetometer were 6 m above the sea floor, then the distance of the target's location from the first anomaly calculates as

$$x_1 = \left(\sqrt{100\text{m}^2 \cdot \beta^2 + \left(136\text{m}^2 \cdot \beta - 36\text{m}^2\right) \cdot (1-\beta)} - 10\text{m} \cdot \beta\right) \Big/ (1-\beta) \text{ with}$$

$$\beta = \left(\frac{B_{A2}}{B_{A1}}\right)^{2/3} = 2^{2/3} = 1.587 \text{, hence } x_1 = 6.43 \text{ m.}$$

3.5.3 Target estimation

Figure 30 shows ten magnetic targets where the mass, position and material of the target are known. These test data will be used in conjunction with the dipole approximation to evaluate typical material properties.

Target ID	Target Description	Target Mass (kg)	Slant Range (m)	Total Amplitude (nT)	Peak Height (nT)
G7 CM0014	9 lb Armstrong pattern cast iron gun Ratio L/W 5.6:1	1,220	11.5	9.5	6.0
G8 CM0015	32 lb Blomefield pattern cast iron gun Ratio L/W 5.1/1	2,845	14.3	7.0	3.0
G10 CM0064	32 lb Blomefield pattern cast iron gun Ratio L/W 5.1/1	2,845	11.3	7.0	4.5
G9 B6/2097	32 lb Blomefield pattern cast iron gun Ratio L/W 5.1/1	2,845	11.0	20	14
G9 15/4448	32 lb Blomefield pattern cast iron gun Ratio L/W 5.1/1	2,845	8.2	22	12

Target ID	Target Description	Target Mass (kg)	Slant Range (m)	Total Amplitude (nT)	Peak Height (nT)
CM0221	Round Crown wrought iron wrought iron Anchor	1,200	15.1	6.0	4.0
CM0242	Angle Crown Anchor	560	16.4	1.7	1.0
Elk	Iron Trawler L108' W21' Ratio 5.1:1	181,000	30.0	300	212
Helene	Iron steamer Note superstructure and deck now missing L73m W11m Ratio 6.6:1	1,567,000 (GT)	30.0	460	216
Derwent	Type 12 frigate	2,100,000	225.0	14.8	

Fig 30 Test targets where the mass and position of the target are known. Data were collected by the ADU, CISMAS, and Peter Holt. Data from the Derwent were taken from Green (2003, 70)

The cast iron guns were all found during the *Colossus* Debris Field Survey (DFS) and were all manufactured during the last half of the 18th century. The two iron anchors were also found during the DFS, but were not necessarily of the same date as Colossus. The *Elk* was an iron trawler which sank off Plymouth in 1902. The *Helene* was a late 19th century iron steamer torpedoed off the north coast of Cornwall during World War One. For further calculations the aspect ratios of the two anchors were assumed as 2:1 although such slight elongation is not necessarily a good approximation of their shape.

Data for the *Derwent* were taken from Green (2003, 70) who included them as case study for aerial magnetic data (hence the large distance to the target). The Type 12 frigate was of 2100 tonnes (iron hull with only 1% aluminium), 112.8m long and 12.5m wide (i.e. with an aspect ratio of 9.0). Exactly what mass the 2100 tonnes describe is unclear. All other magnetometer test data were collected using an EGNOS enabled GPS (no differential or RTK corrections). The actual positions of the targets were established using the same GPS unit. This, along with the layback calculations used to position the magnetometer towfish means that there is some inherent error in the quoted slant ranges from towfish to target. In order to refine the table of test targets data need to be collected using RTK GPS with an acoustic tracking system attached to the magnetometer towfish. That said, these are the best test data we currently have available.

The measurements were used to calculate the numerical constant k of the omni-directional dipole equation and from this the respective Hall Parameter (ie taking the aspect ratio into account) and the mass specific magnetic susceptibility, using the aspect depression γ and an underestimation factor u of 0.7. The results are shown in Figure 31.

Target ID	***Target Description***	***Aspect ratio*** α	***Target Mass*** [kg]	***Slant Range*** [m]	k [nT m^3/kg]	***Hall Parameter*** [nT m^3/kg]	***Aspect Depr.*** γ	***Mass Specific Magnetic Suscpet.*** χ [10^{-3} m^3/kg]
CM0014	G7 - 9 lb Armstrong	5.6	1220	11.5	11.8	2.1	0.93	0.19
CM0015	G8 - 32 lb Blomefield	5.1	2845	14.3	7.2	1.4	0.93	0.11
CM0064	G10 - 32 lb Blomefield	5.1	2845	11.3	3.6	0.7	0.93	0.06
B6/2097	G9 - 32 lb Blomefield	5.1	2845	11.0	9.4	1.8	0.93	0.15
10/942	G9 - 32 lb Blomefield	5.1	2845	9.4	5.3	1.0	0.93	0.08
15/4448	G9 - 32 lb Blomefield	5.1	2845	8.2	4.3	0.8	0.93	0.07
CM0221	Round Crown Anchor	2.0	1200	15.1	17.2	8.6	0.98	0.26
CM0242	Angle Crown Anchor	2.0	560	16.4	13.4	6.7	0.98	0.20
Elk	Iron Trawler L108' W21'	5.1	181000	30.0	44.8	8.8	0.93	0.70
Helene	Iron Steamer	6.6	1567000	30.0	7.9	1.2	0.91	0.13
Derwent	Type 12 frigate	9.0	2100000	225.0	80.3	8.9	0.87	1.35

Fig 31 Material parameters, calculated from measured data and using the omni-directional dipole approximation

The table shows that the values derived for Hall's Parameter scatter between 0.7 and 8.9 nT m^3/kg (if the anchors had been assigned an aspect ratio of 1:1, the range would have extended to 17.2 nT m^3/kg). Clearly, using a single parameter for the estimate cannot reproduce the measurements well. If one had to choose a single value within the range of possible parameters, Hall's Parameter of 10 nT m^3/kg is as good as any.

It appears that there is some grouping within the values of the magnetic susceptibility. All guns have values between 0.06 and 0.19 × 10^{-3} m^3/kg while the two anchors have a higher magnetic susceptibility of 0.20 and 0.26 × 10^{-3} m^3/kg, respectively. It can be speculated that this is due to the stronger magnetic properties of wrought iron. The iron trawler and iron steamer have values of 0.70 and 0.13 × 10^{-3} m^3/kg, respectively, spanning a wide range of possible magnetic susceptibility values. The *Derwent* produces an extremely high magnetic susceptibility value which might be related to inaccurate estimations of mass and size, or to deviations of the estimates for the high altitudes of an aerial magnetic survey.

The analysis shows that material properties can vary considerably and the estimation of target parameters can hence be difficult. If the altitude of the magnetometer towfish over the target is know the mass can be estimated only with the same uncertainty as is inherent in the spread of material properties, roughly a factor of 10. If better estimates of the material properties can be made, such mass predictions can be improved. If the mass of magnetic material is known or can be reasonably estimated, the distance to the target can be calculated as $d = \sqrt[3]{k \cdot w / B}$. Due to the third root, uncertainties in the parameters lead to smaller variability in these estimates. For example a variation of a factor 10 in the material constants (k or w) only leads to variations in d by a factor of ca. 2. Ultimately, this seems the only justification for using a single value for Hall's Parameter: depth estimates will not be wrong by more than about a factor of 2 whatever the value. However, mass estimates may be wrong by up to a factor of 10.

		Total Deflection 1:1		Total Deflection 5:1	
Target ID	Target Mass (kg)	Est. Mass (kg)	Error (%)	Est. Mass (kg)	Error (%)
CM0014	1220	1444	18.4	288	-76.4
CM0015	2845	2047	-28.0	409	-85.6
CM0064	2845	1010	-64.5	202	-92.9
B6/2097	2845	2662	-6.4	530	-81.4
15/4448	2845	1210	-57.5	242	-91.5
CM0221	1200	2025	68.8	405	-66.3
CM0242	560	750	33.9	150	-73.2
Elk	181,000	810000	347.5	162000	-10.5
Helene	1567,000	1242,000	-20.7	248,400	-84.1

Fig 32 showing mass predictions for the test data using the Hall equation

Figure 32 shows the predicted mass for the test targets outlined in Figure 33 at a ratio of 1:1 and 5:1 using the Hall equation. In every case except one (the *Elk*) the prediction for 1:1 ratio – irrespective of the actual ratio of the target, is the better estimate. This confirms that the ratio correction for the Hall equation should not be used.

The Hall equation has been widely used to construct tables of distances at which various targets can be detected (for example Dix *et al* 2008; Green 2003; Hall 1966). These tables are an invaluable aid in survey planning – but the limitations discussed above should be born in mind.

The Hall equation has also been used to give an estimate of target mass (Camidge and Randall, 2009). Although there are potential problems in using the Hall's equation to estimate mass (see above) in practice these estimates have proved to be useful in establishing an approximate target mass. When estimating target mass the actual position of the target will only be known if another survey technique has also identified the target (for example side scan sonar). If this is not the case, or a positive correlation cannot be established, then the towfish altitude will need to be used instead of the towfish to target slant range. In practice this still leads to a useful estimate of the target mass. Figure 33 below shows the towfish altitude used to estimate target mass for the test data set. With the exception of the data from the *Elk* the approximations are close enough to be useful.

Target ID	Target mass (kg)	Fish altitude (m)	Estimated mass (kg)
CM0014	1220	10.6	1131
CM0015	2845	10.7	858
CM0064	2845	10.2	743
B6/2097	2845	10	2000
15/4448	2845	7.5	928
CM0221	1200	13.4	1444
CM0242	560	16.1	709
Elk	181,000	30	810000
Helene	1,567,000	30	1242000

Fig 33 Table showing mass predictions for the test data using the towfish altitude

3.5.3.1 Estimating slant range

A technique for estimating the slant range (the distance from the towfish to the target) has been reported in various papers, for example by Breiner (1973), This is sometimes referred to as Full Width at Half Maximum (FWHM) and consists of measuring the separation of the positive deflection at half its height on a time series plot (see Figure 34 below).

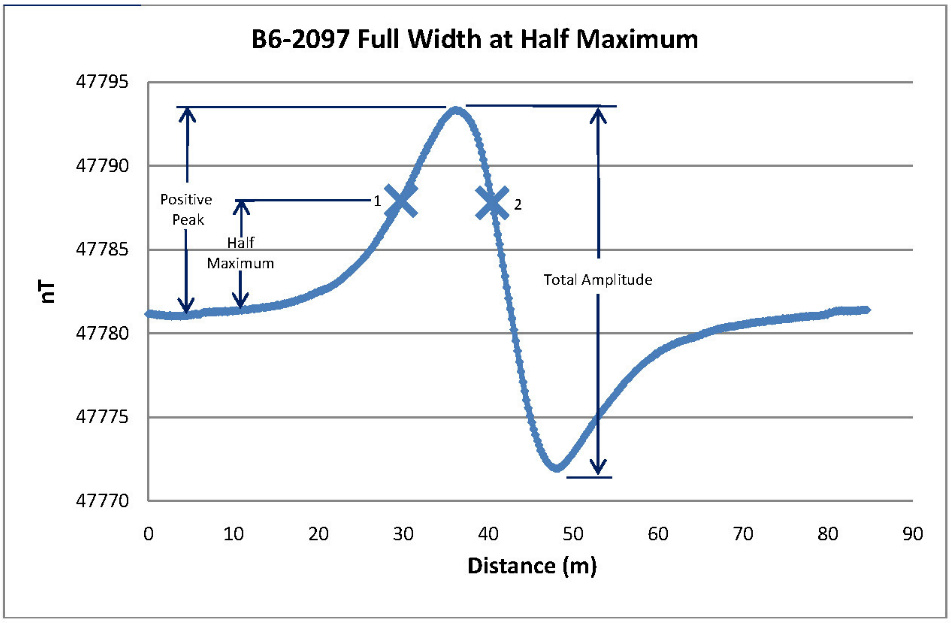

Fig 34 The distance between points 1 and 2 on the time series plot of the magnetometer signal is used to calculate an approximation of the slant range between the towfish and the target

The result is an approximation of the slant range (distance between the towfish and the target). If the towfish did not pass directly over the target then the position of the target relative to the towfish is unknown.

Target ID	Target Description	Range (m)	Actual Slant Range (m)	Est. Slant Range (m)	Error (%)
CM0014	Gun 7	4.5	11.5	27.0	134.8
CM0015	Gun 8	9.5	14.3	16.4	14.7
CM0064	Gun 10	4.8	11.3	9.0	-20.4
B6/2097	Gun 9	4.5	11	10.9	-0.9
15/4448	Gun 9	3.2	8.2	8.9	8.5
CM0221	Round Crown Anchor	7	15.1	12.4	-17.9
CM0242	Angle Crown Anchor	3	16.4	5.6	-65.9
Elk	Iron Trawler	0	30	30.5	1.7
Helene	Iron Steamer	0	30	29.5	-1.7

Fig 35 Table showing calculated and actual slant ranges for test data

3.5.3.2 Sample target

1. Small steel wreck in shallow water

The time-series plot (Figure 36) below shows the magnetic anomaly caused by the wreck of the trawler *Elk* in Plymouth Sound, the *Elk* was 108 feet long, 181 tons and was built in Hull, England in 1902. The *Elk* sank in 1940 after hitting a mine and now sits upright in 30m depth on a sandy seabed, lying with her bows to the north-west, largely intact but missing the upper deck superstructure. The trace below was collected on 19th March 2007 at 18:00 on a run directly over the top of the wreck from South to North using a Geometrics 881 caesium magnetometer recording at 10 Hz sample rate.

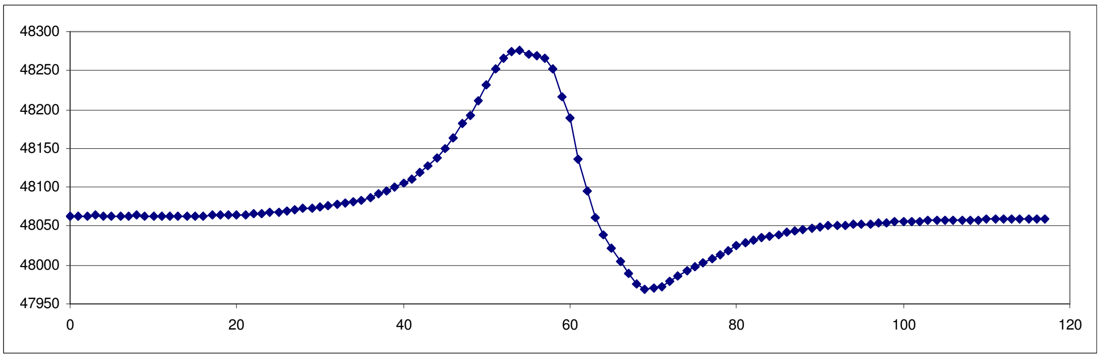

Fig 36 Times series plot caused by the wreck of the Elk

The anomaly shows a positive peak of 212 nT and a negative peak of 90 nT and a fundamental wavelength of approximately 36 seconds or 90m.

This anomaly is very easy to identify as the noise level is very low at around 2nT and the signal level is 100 times larger. The sample rate was high at 10Hz and the large size of the target produced over 60 measurements over the length of the target. The anomaly shows a positive peak to the south and a smaller negative peak to the north, as expected for a south-north run over a target in the northern hemisphere.

Direction of run over the anomaly, show with *Elk* contours

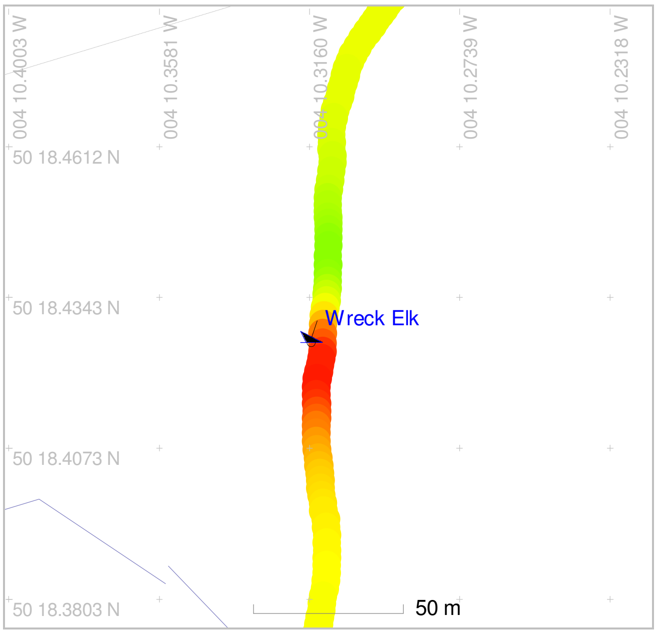

Fig 37 Run E to W over north peak, south peak, middle

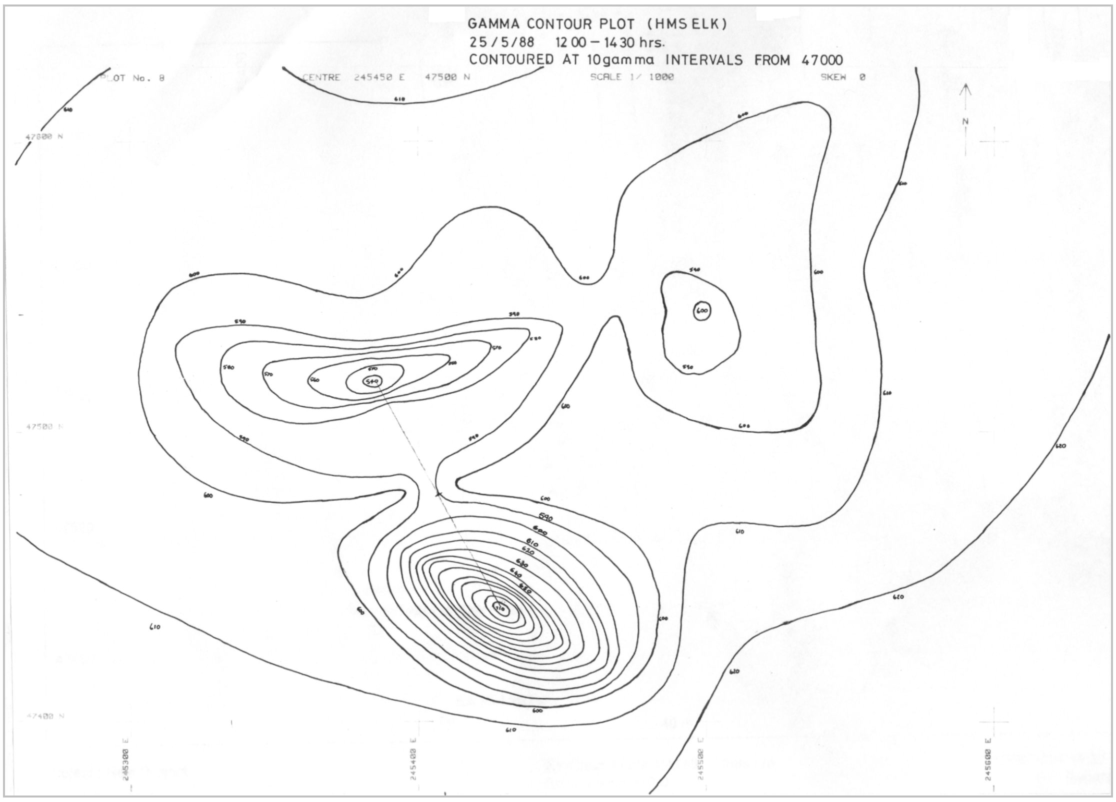

Fig 38 Elk Gamma Contour Plot, University of Plymouth 1988

3.6 Deployment

3.6.1 Towfish altitude and runline spacing

Marine magnetometers measure the ambient magnetic field; this can be affected by a number of factors, including iron objects on or beneath the seabed. The magnitude of a magnetic anomaly depends on the target's mass and is approximately inversely proportional to the cube of the distance from the target to the magnetometer (see above, Section 3.5.2) and (Hall 1966). In practice this means that the maximum size of an iron object which can be detected is determined by the distance from the object to the magnetometer. The two main survey parameters which affect this distance are the altitude of the magnetometer above the seabed (and target) and the distance between survey run lines (see Figure 39 below). These two factors need to be considered together.

In order to optimise the size of target which can be detected by the survey it is desirable to tow the magnetometer towfish as close to the seabed as possible and to use small runline spacing. However in practice a compromise must be reached. The danger of hitting the seabed or the target with the tow fish means that a reasonable separation between the seabed and the towfish must be maintained. What is reasonable will depend on the nature of the seabed, the prevailing sea conditions and the courage of the operator. The run line spacing will also affect magnetometer to target distance, here a balance must be reached between how long the survey will take to complete against the minimum acceptable detection mass. See Section 3.5.1 for expected archaeological targets.

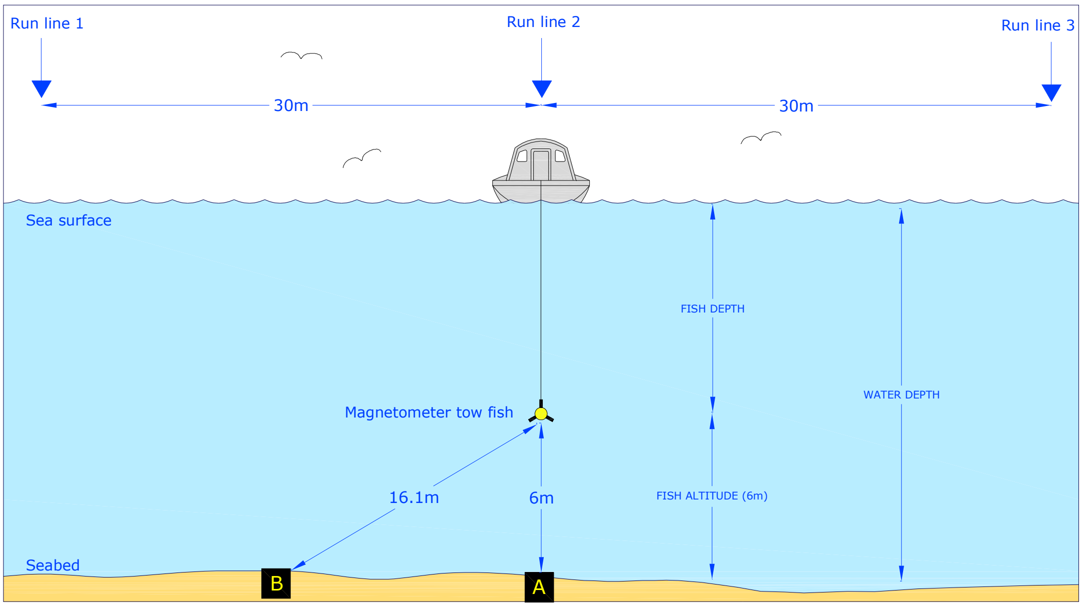

Fig 39 Showing the effect of run line spacing on magnetometer to target distance

Using the run line spacing (30m) and minimum fish depth (6m) recommended by Dix *et al* (2008), results in a magnetometer to target distances of 6m for targets on the run lines (target A in Fig 39 above) and 16m for targets between the run lines (target B in Figure 39 above). This means that in fact the survey is of variable sensitivity – in the example above the minimum mass of iron detectable varies from about 100kg at the run lines to over 2000 kg at the midpoint between run the lines (taking 5 nT as the minimum detectable deflection and using Hall's equation). An illustration of the significant effect run line spacing has on sensitivity (minimum target mass detectable) is to half the run line spacing in the above example (from 30m to 15m). In this case the minimum mass detectable midway between the run lines falls from over 2000kg to 440 kg, the minimum mass detectable on the run lines stays the same at 100kg, thus the differential sensitivity for 6m fish altitude is 20:1 for 30m line spacing and 4.4:1 for 15m spacing (these ratios are independent from the exact form of the dipole approximation used). This is a very significant difference.

The result is that the smaller targets will only be detected at or near the run lines while between the run lines only much larger targets can be detected. In the 30m run line example above (Figure 39) a half ton target (1:1) midway between the run lines would not be detected, giving a theoretical 1.2 nT deflection, while the same target on the run line would give an easily detectable 24 nT deflection. The greater the separation between run lines the greater the differential sensitivity will be. The effect can be reduced but not eliminated by the use of cross lines; reducing run line spacing will always reduce the differential.

Example target	Mass	Minimum detection distance (5 nT deflection)
		Length /width ratio 1:1
20lb round shot	9 Kg	2.7m
32lb round shot	14.5 Kg	3.1m
Small anchor	100 Kg	5.9m
Medium anchor	2 tonne	15.9m
Small Iron gun (9lb)	1.25 tonne	-
Medium Iron gun (18lb)	2 tonne	-
Large Iron gun (42lb)	3.25 tonne	-
Iron wreck	10 tonne	27.1m
Iron wreck	100 tonne	58.4m
Iron wreck	1000 tonne	126m

Fig 40 Typical archaeological targets and their minimum detection distances – based on the equation in Hall (1966, 36); similar results are obtained by using the dipole approximation.

What is clear from the table above (Figure 40) is that the smaller archaeological targets are always going to be difficult to detect. A distance from target to fish of 6m will only result in iron masses larger than 100kg being reliably detected (assuming a minimum detectable total deflection of 5 nT).

Distance (m)	Kg
5	63
6	108
7	172
8	256
9	365
10	500
12	864
14	1372
16	2048
18	2916
20	4000

Fig 41 assumes that 5 nT is the minimum reliable detection deflection. The table is based on equation (2) in Hall (1966,36), with a ratio of 1:1. Consideration should always be given to the different detectable mass for objects midway between run lines. The minimum mass detectable can also be calculated using the dipole approximation (see Section 3.5.2)

Where the survey objectives are to locate larger targets such as shipwrecks a different runline spacing may be chosen. To determine the minimum runline spacing to be certain of detecting a wreck, Enright *et al* (2006) analysed magnetometer data collected for a range of 21 shipwrecks. This study demonstrates that the smallest of the wreck sites analysed, a 27m long by 6m wide wooden hulled sailing ship, would be detected on at least one runline at 40m runline spacing and on two runlines at a 20 m runline spacing (Enright *et al* 2006, 129-133).

3.6.2 How can fish altitude be changed?

Two factors are routinely used to alter the depth of the towfish; these are tow speed and length of tow cable. Assuming the magnetometer fish is negatively buoyant the slower the fish is towed through the water the deeper it will go, similarly the greater the tow cable length the deeper the fish will tow. However in practice it often requires a great deal of extra tow cable to effect a relatively small change in fish depth – this can introduce problems of tow fish position uncertainty (see below, layback Section 3.7.3). Similarly reducing tow speed can also bring problems of maintaining a stable course with the survey vessel – most vessels will have a minimum speed at which a stable course can be maintained in any given sea state; this is often greater than the optimum tow speed required to achieve the desired fish altitude – in which case altitude must be altered by other means.

The mass of the magnetometer can be altered by adding or removing ballast weights, either internally or externally. Another technique offered by many manufacturers is the use of a depressor wing, which forces the fish deeper in the water the faster it is towed. It can sometimes be tricky achieving a stable fish altitude using a depressor as small changes in boat speed can cause significant changes in fish altitude. Impacting a £20,000 magnetometer fish on a rocky seabed can be traumatic, expensive and signal the termination of magnetic survey for that project.

Other factors which effect fish altitude (to a smaller extent) are tow cable density and drag and the hydrodynamics of the towfish – these factors are usually fixed for a given model of tow fish. Tide and sea state will also affect fish altitude; tide will affect the effective tow speed, which has already been discussed. Sea state can alter the stability of the towfish.

3.6.3 Measuring and recording towfish altitude

Marine magnetometers usually have at least one method of recording the depth or altitude of the towfish. The two main methods used are:

Depth sensor

The magnetometer is fitted with a pressure sensor; this can be calibrated to give an indication of the depth of the instrument below the sea surface. The altitude of the towfish above the seabed can then be calculated using either bathymetry collected at the same time and corrected for the difference in towfish/bathymetric sensor positions. Sometimes no contemporary bathymetric data is available; in this case the fish altitude can be approximated from the timestamp on the magnetometer data record using chart heights for the towfish position, corrected for predicted tidal height. The latter method is only an approximation.

Sonar altimeter

Some magnetometers have the option of a sonar altimeter, which records the towfish altitude above the seabed directly to the data file. Whatever system is used the towfish altitude must form part of the magnetometer data set – so that mass predictions and position estimates can be performed.

3.7 Positioning

3.7.1 Introduction

As discussed above, the probability of target detection improves as the distance between magnetometer sensor and target decreases. For marine operations, the majority of targets lie on or in the seabed so the aim of any deployment scheme is to get the sensor close to the seabed. The most convenient method for doing this is to deploy the magnetometer sensor on a tow cable behind a boat; other methods are used in special circumstances and are discussed later.

The survey process involves making measurements at known points and in the case of a magnetic survey we need to be able to estimate the position of the magnetometer sensor at each point a sensor measurement is made. The magnetometer is a short range sensor, compared to most other marine geophysical sensors that are available, and the targets to be found with it are often small so the ability to position the sensor accurately is crucial. To be able to position a towed sensor we first have to position the boat, once done we can estimate a position for the sensor on the cable.

The towing arrangement is often a compromise between position accuracy, the size of the minimum detectable target and safety. To detect small targets the magnetometer sensor in the towfish should be as close as possible to the targets but this increases the risk that the towfish will get snagged on an obstruction or be damaged by being inadvertently towed into the seabed. To get the towfish close to the seabed usually requires the amount of tow cable deployed (the layback) to be long and this decreases the accuracy of the estimate of position for the towfish.

In this section we look at the methods used for deploying the magnetometer sensor and the problems of estimating the position of the sensor for each method.

3.7.2 Surface positioning

Positioning vessels at sea became a straightforward process with the advent of the Global Positioning System (GPS) developed by the US Department of Defense. Before GPS was available it was necessary to use radio position fixing systems such as Decca and LORAN if they existed in the survey area or to install your own system if they did not, or to use more primitive methods such as a sextant for positioning. Wide area radio based systems such as Decca provided positions with accuracies in the order of hundreds of metres with quality that could vary according to the time of day or environmental factors. For accurate work it was necessary to install a more accurate local area system such as Trisponder or Syledis, work that could take up a significant part of the project budget. Fortunately, GPS is now readily available providing global coverage with reliable precision so we can deal with this method alone when considering positioning for magnetometer surveys in the future.

GPS receivers calculate the positions using measurements made to satellites orbiting the Earth. The way the measurements are collected and processed can affect the quality of the position fix so the precision of a fix does depend on the type of GPS receiver used; a clear explanation of these issues can be found in Jonkman (2005) and Cross *et al* (1994). With a full satellite constellation available an unaided position fix with a typical commercial GPS receiver is precise to between 15m and 25m. Precision can be improved by monitoring GPS signals at a fixed base station on shore and sending corrections to a mobile receiver, the mobile receiver can then correct the measurements it receives and so compute a better position estimate. This method is known as differential correction and has a range of capabilities depending on the method used. Wide area schemes such as WAAS and EGNOS provide corrections to the receiver via satellite so no additional equipment is required but only improve estimates to 4-5m, although some corrections available by subscription can result in a precision better than

1m. Locally based reference systems that work over smaller areas use radio telemetry to transfer correction information; these can provide metre or sub-metre level precision. With suitable GPS receivers it is possible to calculate positions using the phases of the signals being received from the satellites and the resulting positions estimates can be accurate to millimetres, this is known as Real Time Kinematic (RTK) positioning. So a range of position quality is available to the surveyor with cost and complexity increasing with precision.

GPS Receivers most usually export position information over a serial link to a computer running a data collection program. The frequency, quality and latency of the available position information will affect the quality of the position fix for the boat. With lower cost receivers there may be limitations on the position update rate available as the position update rate can degrade if the receiver is trying to output too much information. Reducing the number of sentences being transmitted may help alleviate this problem as will increasing the baud rate selected for the link. A related problem is latency in the position fix, here the receiver reports positions that are late and were actually valid a few seconds ago. Many standard serial sentences include a time stamp that defines when the fix was valid however lower cost receivers may only report the current time in the message, not the actual time of the fix. More expensive GPS receivers have very little latency so the problem occurs less often. The effect of this delay is only noticeable when a target is detected on the same survey line run in opposite directions; if the positions are late the apparent position of the same target on each run will be shifted backwards in the inline direction.

The number of decimal places given in the position report needs to be sufficient for the expected precision of the position fix. The resolution of the position given in the sentence from the GPS receiver defines an artificial limit to the precision of the fix. For example, given a position in degrees and minutes at 50 degrees latitude (off the south coast of England) the apparent precision for different position resolutions are:

Decimal places	Latitude	Longitude	Example
1	185.0m	118.0m	50° 18.1’
2	18.50m	11.80m	50° 18.12’
3	1.850m	1.180m	50° 18.123’
4	0.185m	0.118m	50° 18.1234’
5	0.0185m	0.0118m	50° 18.12345’

Where the position is given to only two or three decimal places the effect is to see quantization noise superimposed on the boat position. When shown on a 2D plot this looks like random noise in the boat track. For normal survey tasks positions given to four or more decimal places are acceptable.

For very high precision work there are other factors to be considered. The position calculated by the GPS receiver is the position of the antenna, so if the antenna is high up on a large vessel it will be necessary to compensate for any offset when calculating positions for other points on the boat.

3.7.3 Layback

For most marine magnetic survey work the magnetometer sensor is most often deployed in a towfish towed on a cable behind the boat. The towfish may be towed from a fitting at the front (nose tow) or from a bracket at the centre of gravity of the towfish (CofG tow). The magnetometer may also be towed behind a side scan sonar towfish, connected to it using a short cable, as this means only one tow cable has to be managed for both instruments. As discussed above in Section 3.6.1, the best results of the survey can be obtained by getting the towfish close to the seabed and this requires sufficient cable to be paid out to allow the fish to achieve the desired depth. The magnetometer also has to be deployed sufficiently far from the towing vessel to be away from the effects of the magnetic field of the vessel itself. However, the estimate of position for the fish becomes more uncertain as the cable length increases so a compromise is needed between acceptable position error and the ability to detect smaller targets.

The surface positioning system provides a position for the tow vessel in real time and from this position we can calculate a position for the magnetometer sensor. Two methods are available, the first is to estimate the position by calculation or we can measure the position of the fish directly using an underwater acoustic positioning system. Positioning using a sub-sea positioning system is discussed in a following section; here we will look at estimating position by estimation.

To estimate a position we need to consider what happens to an object towed behind a boat and what affects its position. Magnetometer towfish are most often towed from a point on the stern of the towing vessel (the tow point) and it is from here that the cable starts for the process of estimation. The position of the tow point can be easily calculated knowing the offset distances between the antenna and the tow point in the forward and starboard directions as well as the measured heading of the vessel. For simplicity, with smaller vessels or for lower precision work the difference in position between antenna and tow point in the forward direction can just be added to the length of cable deployed. For some operations it is possible to move the GPS antenna so that it is directly over the tow point and so remove another potential source of position error.

The tow cable attached to the tow point then trails behind the boat and into the water, where the length of cable deployed is known as 'layback'. Any object towed behind a moving boat will take up a position in the water where the forces affecting it balance out, the primary forces being gravity pulling the towfish and cable down, the forwards and upwards pull on the cable from the tow vessel and the drag on the tow cable pulling it backwards and upwards (Kamman and Nguyan 1990). The factors affecting the downward forces are straightforward and depend largely on the towed object and cable mass. The factors affecting the resistance forces are more complicated as they are a function of the density of seawater, the cross sectional area of the towline, the horizontal velocity of the towline through the water and a composite drag coefficient (Myers *et al* 1969). The upward force increases as the vessel speed increases so the towed body will rise if the towing boat speeds up, so the height of the towfish above the seabed (its altitude) can be controlled by changing the speed of the boat. For a given length of tow cable there is a range of boat speed which can be safely used and going above this speed can bring the towfish to the surface, sometimes with spectacular but damaging results as the towfish leaps out of the water. Towing too slowly can cause the fish to drop to the seabed where it can be damaged by impact or snagging; this can be a particular problem when turning a towing boat.

The upward force is also a function of the total cross sectional area of the cable and towfish being towed through the water. This means that we can affect the position of the towfish by using different lengths of tow cable and by changing the diameter of the cable itself. Which is dominant between the cable and the towfish depends on the size of the fish and the length of cable deployed, but in general it is necessary to have a thicker cable to support the weight of a larger towfish so this increases cable drag. For all but the shallowest tows it is the cable drag that dominates so thinner tow cables are preferred. In simple terms, the depth of the towfish and the distance the towfish lies behind the boat increase as the tow length increases but the relationship between the position taken up by the towfish and the length of cable deployed is complex as the tow cable takes up a catenary shape in the water.

The effective flow of water past the cable determines the cable shape so movement of the water itself will have an effect. This is particularly noticeable when working in a river or in the sea where tidal flow is significant. When heading into the current the towfish will tend to tow higher for the same boat speed over ground than when heading down current. Where the current is a significant portion of the desired survey speed it can sometimes be difficult to sail down current slowly enough to gather measurements at the correct rate, here the solution is to only collect measurements with the boat sailing into the current. When heading across the direction of flow the towfish will be pushed downstream irrespective of the direction of tow, this needs to be taken into account when computing the position for each measurement.

Some of the drag on the cable is caused by uneven water flow past the cable so this can be reduced by adding a fairing to the cable to smooth the water flow. The benefits of reduced drag are often compromised by increased handling problems caused by having the fairing attached to the cable itself.

3.7.4 Along track errors

Once the position of the boat has been estimated along with an estimate of the position error, the position of the towfish can be calculated. The computation of position of a towfish on a tow cable can be done in a simple way using trigonometry or by using a cable tow model. The additional position uncertainty incurred in using the simple method increases as tow cable length increases so the simple model is only valid for shorter tow lengths.

The horizontal distance between the towing boat and the towfish is a function of the length of tow cable deployed and the depth of the towfish. The simple model assumes that the tow cable runs in a straight line between the tow point on the boat and the towfish. If we consider a boat travelling in a straight line at a constant speed we can estimate the horizontal distance behind the boat for the towfish as:

$$\text{Distance} = \sqrt{\text{cable length}^2 - \text{fish depth}^2}$$

The length of cable deployed behind the boat can be measured and the depth of the towfish is usually reported by good magnetometer instruments. If the depth is not available from the magnetometer then it will have to be estimated, further increasing the uncertainty in the position of the towfish.

A better model of the tow cable accounts for the catenary shape taken up by the cable in the water. For a given towfish depth and length of cable deployed this model calculates a position for the fish closer to the boat, as the catenary curve path is always longer than the direct distance between tow point and towfish.

With either method we obtain an estimate of the horizontal distance for the towfish behind the boat and from this we can calculate the position for the towfish knowing the position of the boat. The simplest method is to assume that the towfish is behind the boat at the calculated horizontal distance off and at an angle given by the course made good for the boat. The course made good is the angle of the boat as it moves across the seabed, the heading of the boat should not be used as boats rarely move exactly in the direction they are actually heading. This simple model works if the boat is travelling in a straight line; deviations to this line show up in the computed fish position as exaggerated movements of the boat's original track. A more realistic model is to assume that the towfish actually follows the boat track at the calculated distance off. To calculate the position we can integrate or sum the distances between each previous horizontal position fix for the boat until the desired distance back has been reached, this position is then the estimate of position for the towfish at that time. This method works well when the boat is towing in straight lines but also when the track includes shallow turns and 'wobbles' that happen when steering a vessel along search lines by hand. The method is less effective during tight turns as the actual track of the towfish does not follow the boat as the fish tends to try and turn in a tighter circle. However, it is better not to use magnetometer data recorded during turns for other reasons so this limitation is not a problem in practice. Other methods for computing position for the towfish that involve calculating towfish speed over ground should be avoided as they fail to work properly when the boat position is noisy, as can happen with lower grade GPS receivers.

Using the integration method we can obtain a realistic estimate of position for the towfish. The estimate of position error for the towfish is obtained from the sum of the position errors in the calculation. The most important factor to consider is that the position error for the towfish will always be larger than the error associated with the boat position (unless a seabed referenced sub-sea tracking system is used). Positions given by GPS receivers are only an estimate of position and in each case the value should be seen as being plus or minus the expected precision. The achieved precision is hard to determine with any certainty but testing the unit in a fixed position on land will give an idea of the position quality. In practical terms this means that you cannot successfully run search lines 5m apart using a GPS receiver that is only 10m accurate.

To the estimate of error for the boat we need to add the uncertainty in towfish horizontal position caused by limitations in the cable model. These errors are a function of tow cable length and are difficult to estimate without calibrating the system using an acoustic positioning system. The calculation relies on a number of factors which need to be measured accurately to obtain good positions:

- Distance between tow point on the boat and the sensor on the magnetometer
- The offset distances between the tow point on the boat and the GPS antenna
- The fish depth sensor offset and scaling
- Boat position latency

Two types of errors occur, random errors that appear as noise in the position and offset error that appears as a fixed shift towards or away from the boat. Little can be done about random errors other than improving the quality of the position fix for the boat. Along track offset errors can be estimated and corrected given a set of operating conditions, however the exact source of the error is hard to determine as the effects of errors in any of the factors above have the same effect. To determine if an offset error exists we need to run the boat across a small magnetic target in a straight line in opposite directions, the error will show up as a shift in the position of that target in the inline direction. The error value is half the computed horizontal distance between the targets measured on each run. This value can be applied to the layback distance, effectively shortening or lengthening the apparent cable length.

3.7.5 Cross track errors

Cross track position errors are errors across the direction of tow. As with along track errors the position error for the vessel determines much of the random error in this direction but there are offset errors to consider too.

The tow model described above for estimating the position of the towfish assumes that the towfish follows the track of the boat. However, the fish is decoupled from the boat by a flexible cable so some of the cross track motion of the boat will not be copied by the fish, especially if the tow cable is long. This effect can be modelled by applying a low pass filter to the fish position to dampen out the motion but at best this can be considered an approximation.

Any motion of the water across the track of the boat will tend to push the cable and towfish in the downstream direction. Where the water flow is consistent this results in the fish position being offset from the computed position for the whole survey. Where the flow is variable, as with tide induced currents, then the position of the fish across track will vary according to when the measurements were made and unfortunately this is not easy to correct.

Another source of error are variations in the shape of the cable or towfish or the method of tow cable attachment as they can cause the towfish to sit to one side of the survey line. The offset will be to one side of the line with the boat run in one direction and to the other side when run on a reciprocal heading, this causes variations in the separations between actual fish track on alternate lines.

Cross track errors are hard to correct as they are hard to measure without the use of an acoustic positioning system. Running cross lines at 90 degrees to the original survey lines may help detect the problem but for a whole survey this doubles the amount of survey lines to be run. Where possible, cross track error should be minimised by careful rigging of towfish and tow cable and by running survey lines in the direction of expected water currents.

3.7.6 Depth errors

The ability to measure the altitude of the magnetometer towfish above the seabed is a critical factor in the ability to detect small targets, the ability to estimate target size and in the safety of the towfish itself. We have seen that keeping the distance between sensor and target small improves the likelihood of detecting the target so for this reason it is better to tow the magnetometer close to the seabed. The danger in doing this is that the towfish may be accidentally towed into the seabed or even into the wreck being searched for which often results in the loss of the fish.

For safe operation we need to be able to determine the altitude of the towfish above the seabed. Seabed depth measurements from the towing vessel provide an indication of the terrain ahead of the fish so action can be taken to increase or decrease fish depth, often the easiest way to do this is to alter the speed of the towing vessel. Some marine magnetometers such as the Geometrics 882 include an altimeter which directly measures the altitude of the fish above the seabed. Other instruments may include a depth sensor which reports the depth of the towfish below sea level; here the depth of water must also be known to be able to calculate the altitude of the towfish above the seabed. An alternative deployment method is to mount the magnetometer on a tow vehicle that can control its own altitude above the seabed, such as a Chelsea Technologies Nv-Shuttle (Verboom 2001). These instruments can be programmed to operate at a fixed depth or a fixed altitude above the seabed and so optimise the altitude above the seabed for the magnetometer.

As with all measurements, those from altitude and depth sensors are subject to errors. As these measurements are crucial to the operation it is recommended that the sensors be checked and calibrated before use.

Altimeter measurements can be checked by holding the towfish on the surface in a known depth of water and comparing the known depth with the measured depth, this should ideally be done at two different depths to check for scale errors. Depth sensors are prone to scale and offset errors so do not report the correct depth unless calibrated. To do this the towing vessel should be stationary in the water and the towfish can be lowered down on its cable over the side of the ship. Two depth measurements should be made, one at half of the operating depth and one at the operating depth for the survey area.

The scale and offset errors can be calculated from the two raw depth measurements reported by the sensor and the two depth measurements based on cable length deployed:

Scale factor = (depth1 – depth2) / (raw1 – raw2)

Offset = (depth2 x raw1 – depth1 x raw2) / (raw1 – raw2)

A better estimate of towfish depth at any time can be calculated from:

Corrected depth = (raw depth x scale factor) + offset

The precision with which the depth measurement is given can be better than a metre but the reported value can contain far greater errors because of incorrect calibration. The strain gauge depth sensors used for making the depth measurements are also susceptible to temperature effects so the magnetometer should be deployed for 15 minutes and allowed to reach the same temperature as the sea water before any measurements are made.

The use of a large sinker weight or a depressor on the tow cable may put the towfish in a position close to and below the boat. Any heave in the towing vessel will couple to the towfish down the tow cable and my cause the fish to move up and down in time with the waves. This motion will alter the altitude of the sensor above the seabed which will affect the sensor to target distance and may also induce periodic noise. The motion can be minimised by using a two stage towing system (Schuch 2005) which increases the length of cable between the depressor or sinker weight and the magnetometer

3.7.7 Acoustic positioning

Models used to calculate towfish position are suitable for shallow water work where tow cable lengths are small or when searching for targets larger in size than the available position accuracy. For effective deep water surveys or surveys with small line separation it is necessary to position the towfish directly using an underwater acoustic positioning system. These systems measure the position of the towfish directly and report that position to the data collection system, effectively working like an underwater GPS receiver for the towfish. The quality of the towfish position estimate is greatly increased leading to better quality surveys and a higher probability of finding the targets being searched for.

As early as 1966 a paper by Hall refers to positioning a magnetometer towfish using one of the earliest underwater acoustic positioning systems, now they are in regular use for high accuracy survey work particularly for aiding the detection of unexploded ordnance (Pozza *et al* 2003; Funk and Feldspars). Now there are two methods of sub-sea positioning that are in common use but only one is really applicable to towfish tracking. The Ultra-Short BaseLine (USBL) method is used regularly for towfish tracking, this uses a transceiver fitted to the towing vessel to position an acoustic beacon attached to the magnetometer towfish. The alternative Long BaseLine (LBL) method provides more accurate positions but uses acoustic beacons deployed on the seabed and thus only works in the area covered by the beacons (Kelland 1989). The systems can be deployed on vessels upwards of 10m length and have been used to track towfish over laybacks of more than 4500m.

A number of suitable USBL positioning systems are currently available and all work in a similar manner. The heart of the system is an acoustic transceiver which is deployed on a pole mounted over the side of the ship or through the ship's hull. The transceiver sends out an acoustic signal into the water at regular intervals, this signal is received by a small acoustic beacon attached to the towfish which in turn sends out an acoustic reply signal. The reply from the beacon is received by the transceiver on the boat, the transceiver records the time between it sending out a signal and it receiving the reply along with the direction the signal was received from. Knowing the speed of sound in water the system can accurately calculate the distance between the transceiver and the beacon. Knowing the direction of arrival of the signal from the beacon the system can also calculate the position of the beacon relative to the transceiver. The more sophisticated USBL systems can also take in positions from a GPS receiver on the boat and use them to calculate the position of the towfish in the real world. The position of the towfish can then be reported by the USBL system to the data collection program, providing very accurate real time positions for the towfish.

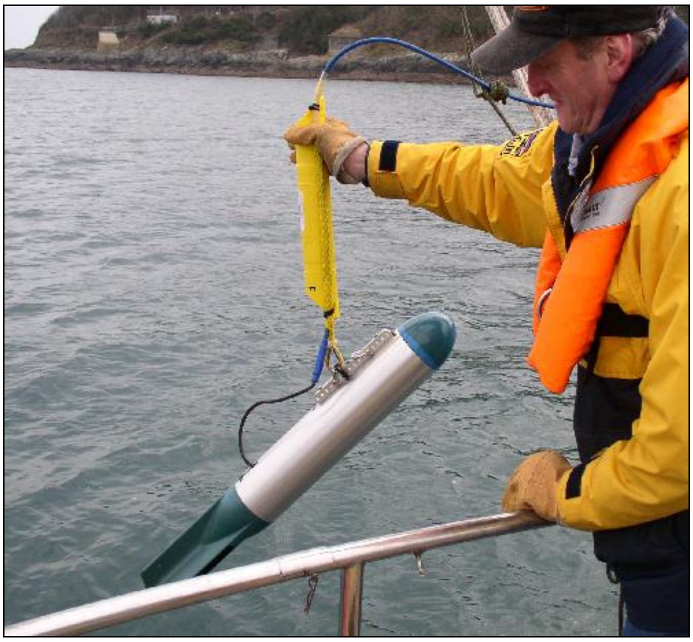

Fig 42 Towfish with yellow USBL transponder beacon

The precision in positioning the towfish achievable using a USBL positioning system is dependant on a number of factors. The position of the towfish relative to the boat is subject to a position error that is a function of distance to between boat and beacon, for better systems the value will be in the order of 0.5% of the slant range but vary according to manufacturer and model. The USBL system needs information about the attitude and heading of the vessel to be able to compensate for the roll, pitch and heading of the boat so a good quality motion sensor is essential for high accuracy work. To compute the position of the towfish in the real world the USBL system needs to know the position of the boat so any errors here are added to the position errors inherent in the USBL system. Alignment and offset errors between the USBL transceiver, motion reference unit and GPS antenna position will degrade system performance and produce lower quality positions however better quality USBL systems can measure and compensate for these errors.

Crawford (2002) used an ORE Trackpoint USBL to track a side scan sonar fish and noted an improvement in repeatability of target positioning of 6.3m with the USBL over 11.0m without. However, it is not clear from the paper how much of the position uncertainty was due to the surface positioning system. It was also not clear if the USBL system had been calibrated correctly with respect to the attitude and heading sensors, a crucial process that has to be undertaken if measurements are made to determine precision.

A significant benefit of the use of an acoustic positioning system is the ability to correct the position of the towfish in real time, as any mis-positioning of the sensor cannot be corrected in post processing. In the situation where water currents or hydrodynamic effects have shifted the position of the towfish away from the vessel track the towfish will not be following the path determined using a simple layback calculation. If the towfish is positioned in real time using a USBL system then the towing vessel can be moved off line to correct for the shift in towfish position and so put the towfish itself back on to the survey line. The availability of real time positioning also allows the use of steered tow vehicles such as FOCUS-2 and Triaxus for deep water, long layback searches. These vehicles can be steered remotely using control surfaces on the vehicle itself allowing the cross-line position and depth of the vehicle to be controlled (Caiti *et al* 2007) putting the towfish in the optimum altitude and position for the survey.

3.7.8 Surface deployment

For very shallow water survey work the risk of towing the magnetometer into the seabed can be high so the towfish has to be towed on the surface. In extreme cases where the search area is in amongst submerged rocks it may be necessary to mount the magnetometer in the boat itself so the boat can manoeuvre safely (Weiss *et al* 2007; Holt 2008).

For surface towing the magnetometer can simply be slung underneath a few surface floats, a couple of long boat fenders are ideal for this. The cable itself may also need to be kept on the surface using small floats so it does not snag on the seabed or get wrapped around the boat propeller and steering gear. Surface towing is usually performed using small boats as they have a shallow draft and can be used safely in shallow water. The use of a small boat allows the use of short tow cable, particularly if the boat is not made of steel. A Diesel engine is preferred as the ignition systems on petrol engines can create noise on the magnetometer signal. The short tow cable allows more accurate positioning of the towfish, in some cases it is even possible to mount a splashproof GPS antenna above the magnetometer itself so removing any layback error.

Mounting the magnetometer in the boat itself can also be done in situations where towing is not possible. Here the magnetometer will be affected by the magnetic field of the boat itself so any unnecessary ferrous material on board should be removed before starting work. The magnetic anomalies caused by targets near the boat will be superimposed on the field of the boat and the magnetometer will record the compound field value. The reading from the magnetometer in this position will be affected by the heading of the boat so it is suggested that measurements are made in one direction only if possible. Data collected in this way can be difficult to interpret because of the effect of the change of vessel heading on the measured field may appear as valid anomalies.

The main drawback with these methods is that they increase the distance between the targets and the sensor so they are only recommended for use in shallow water.

3.7.9 Diver, ROV and AUV deployment

Targets detected during surface towed searches can be hard to locate if they are buried under a featureless seabed. Targets can be more precisely located by taking the magnetometer underwater.

Divers carrying magnetometers have been used to locate and map buried objects. The Kyrenia ship which lies off the North coast of Cyprus was surveyed using an early development of the proton magnetometer (Green *et al* 1967). A cable connected magnetometer was placed horizontally on the seabed in a grid pattern 28m long and 10m wide with squares every 2m. A similar method was used at Cape Andreas, Cyprus (Green 1973) and on the *Santa Maria de la Rosa* (Green 1970).

The anchor from the 5th Rate Royal Navy frigate HMS *Sirius* which sank during the Battle of Grand Port in Mauritius in 1810 was detected using a towed magnetometer, but could not initially be located as the anchor was completely buried in the seabed. The anchor was finally located by a diver, hand carrying the magnetometer towfish around the estimated location until the peak anomaly was detected. This work eventually led to the excavation, recovery and preservation of the anchor. For this task the diver used an aluminium air tank and the minimum of ferrous dive equipment to keep his own magnetic signature low. The job was hampered by the cable connecting the magnetometer to the surface so using a self-contained untethered magnetometer would have been more practical. A diver held proton magnetometer called Diver Mag 1 is available from JW Fishers, this has a sensitivity of 1nT and sample rates of between 2 and 10 seconds. Quatro Sensing produce a hand held proton magnetometer called Discovery with a sample rate of 5 seconds. Webber developed a diver held version of a Geometrics 882 caesium magnetometer that does not require a tether and can be used by a diver using SCUBA equipment, see Figure 43.

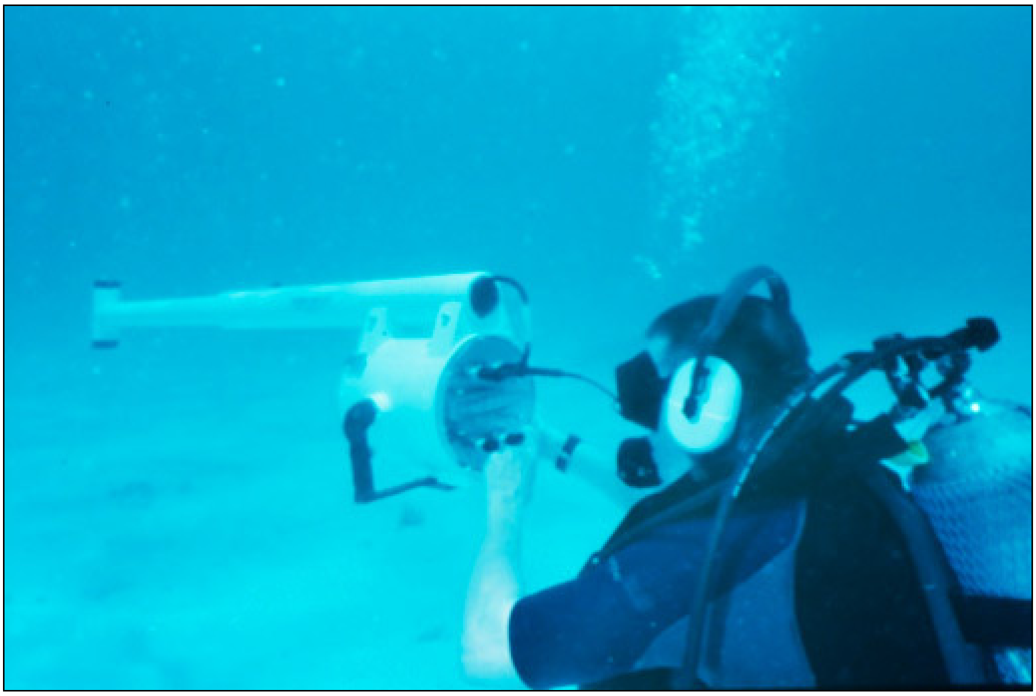

Figure 43 Diver held caesium magnetometer

Magnetometers have been deployed on remotely operated vehicles (ROVs) however the magnetic field of the ROV itself affects the local magnetic field strength and varies as the ROV heading changes, so the signal from the magnetometer changes with the ROV heading. The ROV will also generate large amounts of wideband electrical noise which degrades the magnetometer signal. A large pulse induction metal detector may be used in preference to a magnetometer, these are used by the oil and gas and the submarine cable industries to locate and survey pipelines and cables on or below the seabed at water depths of up to 3,000 metres. Unlike magnetometer-based sensors, the technology used in these systems is unaffected by changes in the heading of the ROV.

An Autonomous Underwater Vehicle (AUV) is a self-propelled, unmanned underwater vehicle that is controlled by an onboard computer (Chance and Northcutt 2001). An AUV is an ideal platform for marine magnetic searches its inherent high precision navigation capability allows it to follow tightly spaced survey lines very accurately and it can maintain a constant altitude above the seabed even in rough terrain. An AUV can operate over a wide area without the need for a surface vessel to be overhead and it can operate in shallow water areas unsafe for conventional towed searches.

3.8 Runlines

3.8.1 Orientation

The orientation of the survey runlines will be determined at the survey planning stage. The most important consideration is usually the topography of the seabed. If the seabed is anything other than level and flat the runlines will need to be aligned along the contours of the seabed in order to maintain a constant towfish altitude and to avoid running the towfish into the seabed.

It is sometimes suggested that runlines should be in a north-south direction in order to maximise the magnetometer signal due to a claimed north south orientation of target dipole anomalies.

> *Magnetic anomalies around the British Isles will normally have a dipole field pattern, orientated North-South. Therefore the magnetic field over an anomaly will have the greatest rate of change in this direction, consequently field lines should preferentially be orientated North-South wherever possible. Cross lines (ie E-W) should be run in the orthogonal direction to the main survey lines at approximately 5 times the line spacing used in the main survey direction* (Wessex Archaeology 2007)

However, in practice this only applies to wrecks which appear to have dipoles aligned predominantly within ± 45° of magnetic north. Individual objects such as guns or anchors (debris) will have their dipole fields aligned with the long axis of the object and will therefore have no particular orientation (Enright *et al* 2006).

3.8.2 Bi-directional runlines

The use of bi-directional run lines is the most time efficient method of completing an area survey as it minimises the distance travelled by the survey vessel whilst survey data is not being collected. If a search area is oriented east to west, for example, and the first run line is undertaken with a westerly heading, it is logical that the next run line should be made with a reciprocal heading. The vessel heading then alternates as such until the survey area is completed.

One problem associated with the use of bi-directional run lines might be evidenced by 'banding' or 'striping' when the magnetometer data is plotted as a contour or colour density map. This is a consequence of heading error which, as discussed in Section 3.4.6, affects the amplitude of the total-field measurements in different ways depending upon the orientation of the instrument (Dix *et al* 2008, 56).

3.8.3 Uni-directional runlines

Uni-directional run lines are all completed using the same vessel heading, for example always east to west. Completing an area survey using uni-directional run lines will reduce 'banding' or 'striping' caused by heading error when using bi-directional runlines as the same heading error will be present on each run line.

Using run lines of a single heading might also be advantageous when sea and wind conditions influence boat speed and, therefore, instrument altitude. It may be preferable to survey into a head wind, which will reduce the boat speed and help achieve a low instrument altitude, compared to a tail wind which might render achieving a suitable instrument altitude impractical. This is not a factor which can be feasibly taken into account when planning a survey however.

Unfortunately the survey vessel must return, following our example, from the western extent of the survey area to the eastern extent before the next run line can be commenced. The use of uni-directional run lines therefore approximately doubles the time taken to complete a survey area.

Whether survey efficiency should be sacrificed in order to complete uni-directional run lines should be dictated by the susceptibility of the magnetometer in use to heading errors (see Section 3.4.6), the prevailing wind on any given day and the necessary survey resolution stipulated in the survey methodology.

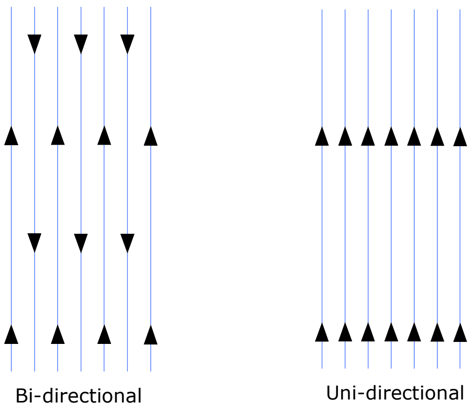

Fig 44 (above left) and Fig 45 (above right) Bi-directional and uni-directional runlines, with survey vessel heading indicated by directional arrows

3.8.4 Grid

More information about an area to be surveyed can be gathered if data is collected over the whole area more than once. Collecting data over an area in a grid pattern does just this; data is collected in a series of runlines parallel to each other then a second series of lines are run but in a direction orthogonal to the first. As discussed above in Section 3.4.2, the density of the data in the inline direction can be higher than in the cross line direction as the first is defined by sample rate and the second by runline spacing. Running a second set of lines at 90 degrees angle to the first will improve the data density in the crossline direction for the area immediately under each cross track and can provide more information about the positions of targets in that direction.

The drawback is that the survey is effectively run twice so takes twice as long to complete. So long as the runline spacing is sufficiently small to be able to detect the minimum target size required the extra lines run in the crossline direction will add very little useful information.

A more useful strategy is to identify the significant targets in real time then to 'box them in' with extra survey lines run in the opposite direction to the tow then in both crossline directions. The line run in the reverse direction can be used to calculate any position offset in the inline direction and the two cross lines can be used to improve the estimate of position in the crossline direction.

Where a magnetic map of the site is to be created some extra cross lines can be useful for levelling the lines run in the inline direction. Data from lines run in opposite directions may vary in their average absolute value and when plotted show a corrugation pattern with alternate lines showing higher and lower values. Levelling is discussed in the section on post-processing.

3.9 Post-acquisition data processing

3.9.1 Target identification

3.9.1.1 Introduction

The simplest use of a magnetometer is to detect the presence or absence of a magnetic source or target. The next level of processing is to use the size of a magnetic anomaly to estimate the target mass or the shape of the anomaly to estimate its characteristics. The anomaly shape can also be used to estimate the distance from target to sensor and in some cases to estimate depth of burial. All of these tasks are limited by the ability to detect wanted anomalies amongst the background noise - magnetic anomalies are the sum of many anomalies both wanted and unwanted.

The measurements from the magnetometers used in marine magnetic surveys record the value of the geomagnetic field at a point in space. Measurements made over a period of time with the sensor moving along a known path represent sampled measurements of the strength of the magnetic field along that path. The magnetic field at any point will be the vector sum of the geomagnetic field plus the field effect caused by any magnetic anomalies present; to this combined field measurement we can add the effects of a number of noise sources. To interpret the results of a magnetic survey we need to correctly identify the targets of interest from the unwanted noise. We can represent the variations in field strength along a runline by plotting field strength against time or distance on a time series graph. We can represent the same information in a number of different ways and these are discussed in Section 3.9.5.

Using time-series graphs we can demonstrate the effect of the addition of the fields:

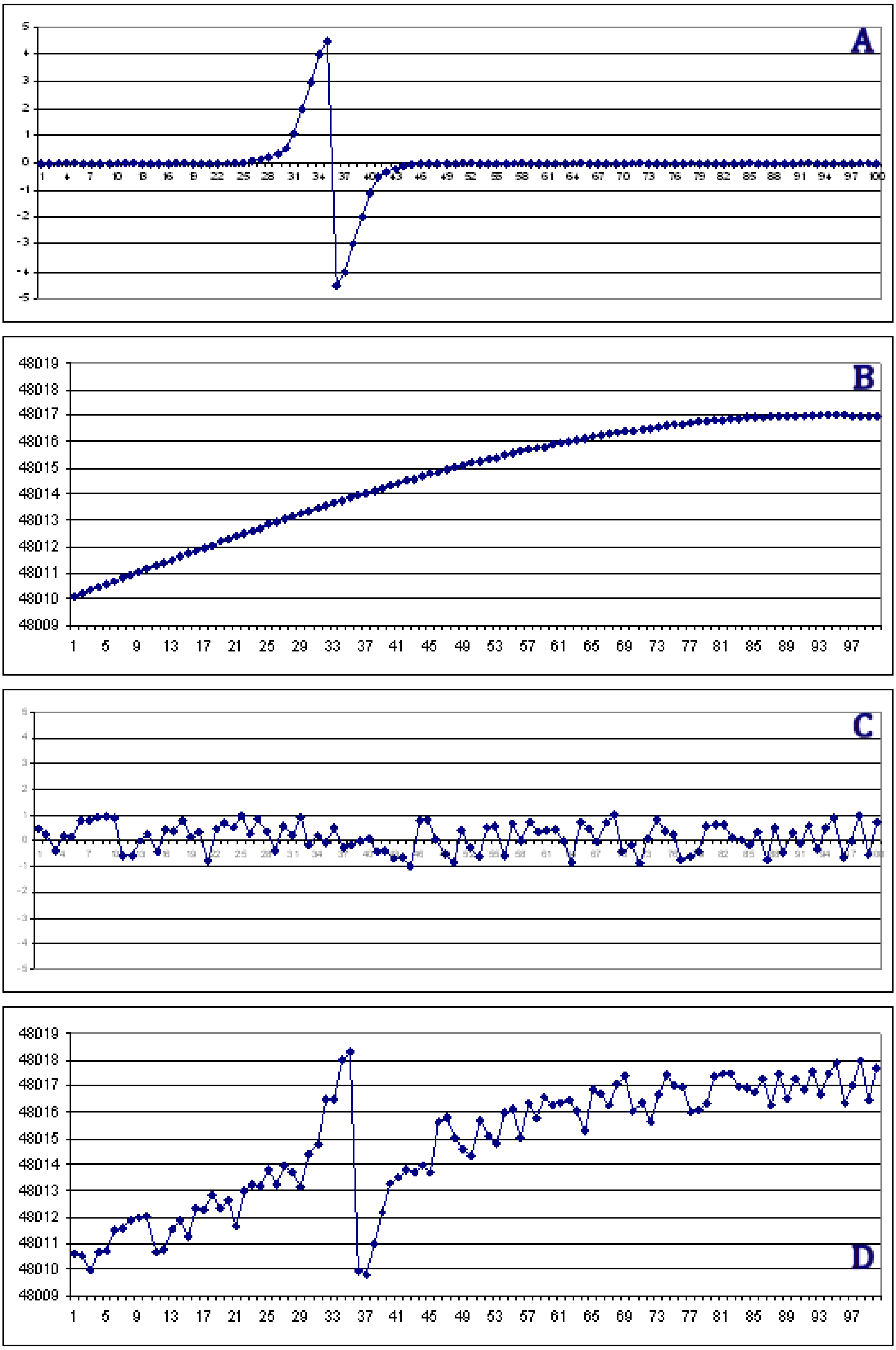

Fig 46 Addition of fields

In Figure 46, the transient signal A shows a typical simulated anomaly. Note that the transient target signal has a short wavelength yet shows a larger range of extreme values, this is usual for the typical small, ferrous targets to be detected in archaeological surveys. The regional magnetic field B varies along the profile to simulate larger wavelength geological effects. The effects of noise from electrical sources, instrument self-noise and diurnal variation are shown in plot C. Plot D shows the sum of the magnetic anomalies in A, B and C; now it is much harder to resolve the signal caused by the target amongst the other noise sources.

3.9.1.2 Sources of noise

Determining wanted signals amongst a number of different types of noise forms the basis of communications theory, this was originally applied to radio communications but the methods used can be applied to any other form of information transfer. The aim is to be able to reconstitute the signal caused by the target by removing the noise, the difficulty is in doing this without severely distorting or even eradicating the wanted signal. The ratio of the amount of measured noise to the amount of measured signal, the Signal to Noise Ratio (SNR), is an important metric as this helps define how easy it will be to separate one from the other. Where the noise level is small and the effect of the magnetic anomaly is large (the SNR will be a large number) the wanted signal is easy to identify but where the noise level is high or the signal level small (SNR is small) then problems occur in identifying targets.

In all cases it is better to increase our chances of detecting a signal by making sure what is recorded has the largest level of signal in the lowest level of noise. Filtering the measurements will always produce poorer results than can be obtained from better data as filtering by its very nature involves the removal of information. We can improve the SNR by making the signal larger than the noise level, for a magnetometer this can be done by getting the sensor closer to the target. We can reduce the noise level in a number of ways depending on the source of noise, so we next need to look at the sources of noise and the effect they have on the measurements.

Noise is any unwanted signal, and for an instrument that measures the Earth's magnetic field there are a number of sources of unwanted signals. These include:

- The Earth's regional magnetic field
- Diurnal variations in the Earth's field caused by the Sun
- Electrical noise sources
- Instrument self noise
- Communications errors between the instrument and the recording system
- Noise induced by waves

What can be considered to be 'noise' in magnetic data depends on the purpose of the survey. For archaeological surveys we are looking for the effects of cultural material on the magnetic field and variations in the Earth's magnetic field caused by geological effects are considered to be noise. Geological surveys are interested in the geological effects and consider the effects of shipwrecks to be noise. This is significant when determining how best to process marine magnetic data and when looking at previous work with magnetometers in other applications.

3.9.1.3 The regional field

The strength of the magnetic field of the Earth varies across the planet and is detected as a long wavelength magnetic anomaly known as the regional field. Superimposed on this are smaller variations in the local magnetic field caused by variations in the underlying geology.

Most rock forming minerals are non-magnetic but some contain enough magnetic minerals to create a magnetic anomaly. For areas of the world lying on a non-magnetic substrate of rocks the regional magnetic field will be a fairly constant value across any typical area defined for a marine magnetic survey as the areas are usually small on a geological scale. The regional field is usually seen as a slowly changing background signal with a long wavelength, but in extreme cases the effect of the underlying rocks shows up as large signal variations with shorter wavelengths. In these areas the effect of a shipwreck on the magnetic field may be swamped by larger variations in the background field caused by geological anomalies.

3.9.1.4 Diurnal variations

Diurnal (or daily) variations in the geomagnetic field are caused by the flow of charged particles within the ionosphere. On normal or quiet days the variation is a smooth change with amplitudes in the order of 20-80 nT over a period of 24 hours. During magnetic storms the variations include short duration, high amplitude disturbances with amplitudes up to 1000nT. The slowly changing variations also include higher frequency micropulsations that vary in duration from 0.3 to 100 seconds and in amplitude from 1 to tens of nT.

Correcting for the effects of regional and diurnal variations is discussed below in Section 3.9.2.

3.9.1.5 Power supply noise

The power supply used for the magnetometer can have an impact on the background noise level as noise generated by the power supply can degrade the signal reported by the magnetometer. This is a particular problem with proton magnetometers but also affects caesium and Overhauser systems so some degree. Noise from power supplies may be at characteristic frequencies such as 50Hz or 100Hz but particular problems occur using low quality inverters to create A.C. mains power from batteries as the harmonics the inverters create can break through onto the measured signal. Other equipment powered from the same battery or a battery charger connected to it can also add noise so it is better to power a magnetometer from an isolated battery. Poor earthing of the power supplies can cause problems where the magnetometer and the logging computer are powered from different sources as the electrical connection via the serial data link can provide an earth loop. The ignition spark from a petrol engine is also strong enough to be detected by a proton magnetometer as are the transmissions from mobile phones and VHF radios.

3.9.1.6 Instrument noise

Another significant source of noise is that created by the instrument itself. All instruments that measure have a lower limit on the precision of the measurements made; this can be seen by making the same measurements many times and noting the variation in values. For a magnetometer we could place it in a fixed position and record the variation in measurements that are recorded over a period of time. What the instrument would record is a combination of all of the sources of noise that affect it, excluding those caused by moving over the Earth and past magnetic debris. The sources of noise for a static sensor include self noise generated by the instrument itself, noise generated from the power supply that feeds the sensor and external effects such as diurnal variation discussed above. The level of background noise recorded in this way, the noise 'floor', effectively defines how small a signal can be detected with that instrument. To be able to reliably detect small magnetic targets at a distance we need to ensure that the background noise level is as small as possible.

Simple proton magnetometers suffer more from external and internal noise sources than do more expensive Caesium or Overhauser instruments. With many simpler systems the tiny electrical signal from the sensor in the towfish is sent back along the length of the tow cable to the magnetometer instrument where it is amplified and processed. Any noise picked up in the cable will be amplified by the instrument itself so care must be taken to minimise electrical pickup. Caesium and Overhauser instruments do the primary processing in the towfish itself and only digital serial data is sent along the tow cable, so electrical pickup in the cable will affect the measurements much less or not at all. Some proton magnetometers also suffer from thermal noise effects where the instrument self-noise level increases with temperature:

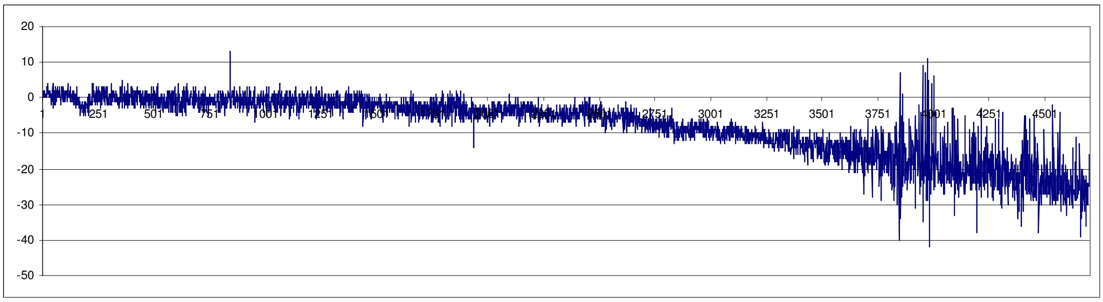

Fig 47 Thermal noise

Figure 47 shows the magnetic field recorded over a period of 3.5 hours with an increase in noise in the later stages due to instrument heating (1Hz sample rate, AX2000 proton magnetometer). To avoid these problems the magnetometer surface unit should be kept in a cool place and out of direct sunlight.

The instrument may also report measurements that are random values or mistakes. Sometimes the instrument will be affected by an external interference causing a single random measurement or 'spike'. In other cases a measurement may not be reported causing 'dropout'. Problems can occur in the exchange of the measurement value from instrument to recording system, the loss of a character on a serial string may result in an invalid string that can be detected and removed but sometimes it results in an invalid measurement.

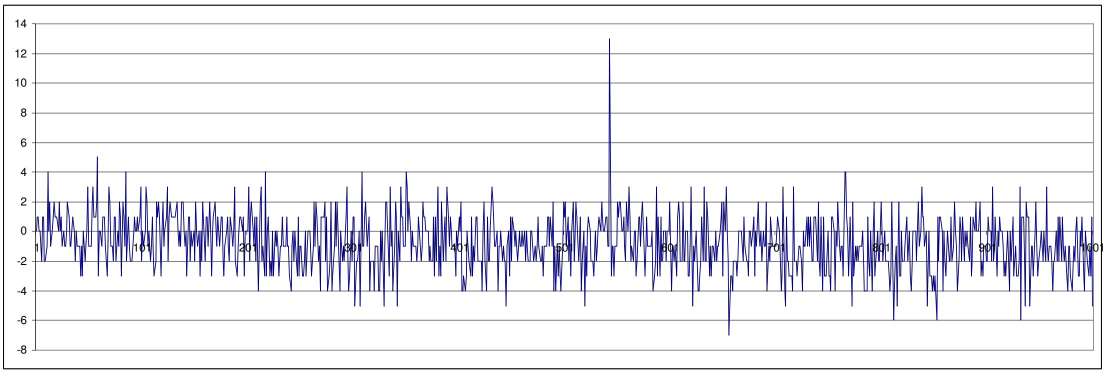

Fig 48 Random background noise with spike

Figure 48 above shows the signal recorded by a static proton magnetometer (Aquascan AX2000) over a period of a few minutes. The signal varies by plus or minus 3 nT but includes a single spike measurement at 13nT. The trace shows the sum of the noise sources described above but can most easily be attributed to instrument noise.

Proton and Overhauser sensor noise levels are also dependant on the ambient field strength and under low field strength conditions their SNR deteriorates (Geometrics 2000).

3.9.1.7 Swell noise

Ocean waves and swells generate magnetic signals caused by the induction of seawater moving in the regional magnetic field of Earth (Nelson 2002). These effects may be significant when searching for small targets as Lilley (2004) measured signals in the order of 5nT using a free floating magnetometer.

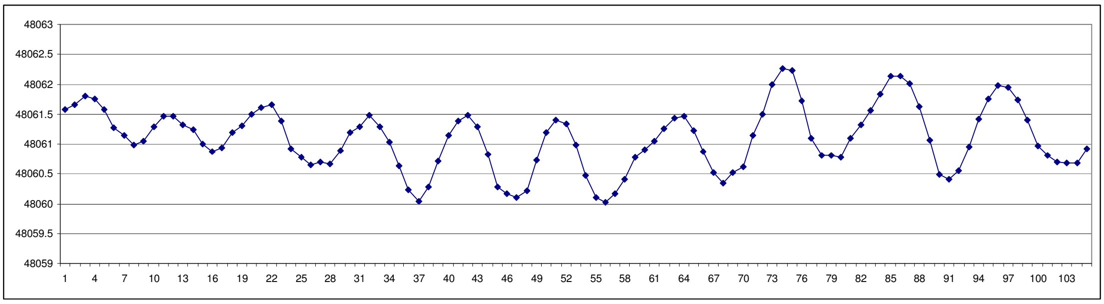

Fig 49 Swell noise

Figure 49 shows the magnetic field recorded by a caesium magnetometer in Plymouth Sound when the sea conditions were rough sea (state 4-5). The trace shows swell noise of 1.5 to 2.0 nT peak to peak at a frequency of 0.1 Hz and a wavelength of 26m.

3.9.2 Regional and diurnal correction

Targets of interest caused by cultural material are often superimposed on a much broader anomaly caused by variations in the earth's magnetic field or by geological sources. Instruments that measure the total field will measure the sum of the effects of both the residual field caused by the target and the background, regional magnetic field (see figure X). The background field value at any point will also change with time because of diurnal variation caused by the movement of the sun. Separation of the residual field that we are interested in requires the removal of the regional field from the total field measurement.

In most cases the wavelengths of these two components vary as the regional field has a long wavelength (small wavenumber) and the target signal has a much shorter wavelength. This difference can be used as a way of separating regional and residual fields. Lower frequency variations in the magnetic signal can be isolated from the data using methods such as polynomial filtering, wavelength filtering using Fourier Transform or wavelet and vertical derivative.

The filtering methods aim to separate the lower frequency components of the signal from the higher, but both regional and residual fields will be composed of a range of frequencies so filtering will not cleanly separate one from the other. The transient waveform caused by the target has an infinite frequency spectrum so any form of filtering will alter the original wave shape. All we can hope to achieve is to separate the regional and residual fields to be able to detect anomalies of interest. Care should be taken when making measurements from filtered anomalies as the filtering process may alter the size and shape of the anomaly.

For small targets that only show up on one or two survey lines then it is often better to process the anomalies separately and treat them as individual targets. The absolute level of the regional field is effectively ignored and all we look at is the short term variation of this background level caused by the target. The product of this processing is often just a simple point with a given position and a given signal strength in nT. This method has the advantage that the transient waveform is not filtered so the shape is unaffected and can be used to make signal strength measurements.

However, when integrating data caused by a large target using data from more than one survey line it is often beneficial to remove the regional field component of the measurement. Measurements made at different times will have regional and diurnal variation effects that will alter the mean field value. These differences can often be removed by high pass filtering the data, this effectively removes the contribution from the regional field and normalises the data to a mean value of zero. Deflections from the mean value are then much easier to identify in a two-dimensional plot when comparing data from different survey runs made at different times across the same location in the survey area.

Changes in the background field caused by diurnal effects can be removed by repeat occupation of the same point at different times. The problem with this method when working at sea is ensuring that the sensor is returned to the same position and same depth with sufficient precision. Any error in the 3D position may cause an inherent difference in the total field that was measured and when processed this may show up as a valid target.

Although the noise added by diurnal variation can be reduced by high and low pass filtering, the components of the noise that are in the same frequency band as the main components of the wanted signal will still remain in the dataset. The effects of diurnal variation can be more elegantly removed using measurements from a base station reference magnetometer. A base station can be set up to continuously record the magnetic field at a fixed point near the survey area while the survey data collection is undertaken. The measurements the base station records can simply be subtracted from the measurements made during the survey, with the measurements synchronised using accurate time stamps recorded with each measurement. The reference and survey measurements are correlated by time so it is important to ensure that both logging systems are synchronised to the same time frame. If the reference measurements are made at a lower sample rate than the survey measurements the correction values can be estimated by interpolation. The base station should be located as close to survey area as possible so the background field measured by the base station is the same field measured by the survey magnetometer. The base station should be located far from contamination by passing cars but in a secure location where it will not be damaged or stolen.

3.9.3 Data processing

3.9.3.1 Introduction

The main aim of the data processing phase of the survey is to take raw field measurements at known position estimates and deduce the locations of magnetic targets within the survey area along with an estimate of the precision of the position. A secondary aim is to estimate properties of the targets such as mass, size and burial depth, then for larger targets it is also possible to produce 2D maps and 3D models of the magnetic anomalies. To be able to identify a target we first have to be able to detect it amongst the noise and then we have to estimate its position.

Some form of filtering is done on all datasets before or during interpretation and the degree to which it is done usually depends on the products required for the survey and the quality of the data itself. Generation of a list of targets and positions is straightforward - if the magnetometer data has a high SNR (is 'clean') then the targets can be identified just by looking at time-series plots of the measurements. The trained eye has a wonderful ability to identify differences in data series even when it is noisy. If the data contains spikes and dropout then these can be removed to make interpretation easier but the same method is then used to identify targets. Little else must be done to the data to be able to estimate target size and mass as these can be derived from the time-series plots and the position estimates for each measurement. If the data contains artefacts caused by geologic effects or high frequency instrument noise then this can be filtered out to aid interpretation. If measurements from adjacent lines is to be compared, plotted or used to create a contour map then more work is needed. Here the measurements on each survey line need to be adjusted so that small changes caused by valid targets are not lost in large scale changes in the background level.

A detailed description of enhancement methods is available in Milligan and Gunn (1997).

3.9.3.2 Position estimation

Usually the first step in processing data of this kind is to deal with position estimation. For a typical marine magnetic survey the magnetometer is towed behind the boat on a cable, so we need to calculate estimates of the position of the towfish when each field measurement was made. We talk about position estimates rather than positions as it is important to see positions as probable rather than exact when post processing. As we will see later, it is possible to draw incorrect conclusions by over-processing datasets and assigning too high a reliance on position quality is a common cause of this.

To calculate the position of the towfish at any time we start with the position of the towing vessel. The position of the tow vessel will most probably be recorded as a series of position fixes from a GPS receiver and these positions will be subject to noise, spikes and loss of data. The quality of the position fix will depend on the quality of the positioning instrument and the operating circumstances (see above, Section 3.7.2) so an estimate of position error should be calculated based on this. This sets the lower bound on the estimate of position error for the magnetic data. Jumps or dropout in the position of the boat need to be removed as they will give an incorrect position for any measurements that use them, the method used to do this is called despiking and is discussed in Section 3.9.3.3 below.

If the position data is too noisy then it may become too difficult to calculate realistic positions for the towfish. Where possible the survey should be re-run and better data collected but sometimes this is not possible so position filtering should be considered. The positions from GPS receivers are already filtered to some degree and care must be taken not to over-filter positions to produce a good looking but unrealistic vessel track. The optimum method for reprocessing a series of positions uses the correlation between the two position components (Easting and Northing or Latitude and Longitude) and the positions before and after the position fix of interest (known as smoothing). It is possible to process one component separately from the other but a better answer will be obtained by processing both together and using the change in position between position updates to provide more information. When filtering in real time only the positions up to the time of interest are available, in post processing the information is there to show what happened next and this can be used to help remove errors. A Kalman filter is often used to compute estimates of position in real time so a Kalman smoother can be used for the same task in post-processing (Yu *et al* 2004).

With good estimates of position for the towing vessel we can calculate estimates of position of the towfish at the same time. If an acoustic positioning system was not used to track the position of the towfish then the position needs to be calculated in the manner described in Section 3.7.3 above. Each position for the tow boat will generate a position for the towfish at the same time; the position error associated with the towfish position will be the error associated with the boat position plus additional error which is a function of the layback. If an acoustic positioning system was used then the position of the towfish will have been calculated in real time although an improvement in the position quality may be obtained by reprocessing.

As caesium and Overhauser magnetometers can generate measurements 10 times per second it will be necessary to interpolate towfish positions if they occur at a lower rate. If the GPS receiver outputs a position once per second then the positions for the intervening magnetometer measurements need to be calculated at the time of each measurement.

Interpolation will also have to be done when using an acoustic positioning system as often they can only report a position once per second. The interpolation process is straightforward in post processing so long as the time of each GPS or APS position and the time of each magnetometer measurement are known to sufficient precision, for 10Hz data the timestamps should be given to 10ms or better.

Post processing legacy datasets raises particular problems that occur less often now GPS is commonplace. Data collected using other surface positioning systems such as Decca will contain positions with much larger errors and this needs to be reported when reporting the position of any target detected during the survey. The same problem occurs with uncorrected GPS positions collected before the year 2000 that have been degraded with Selective Availability as these positions will have a precision of 50-100m. High precision GPS positions may still contain an offset in the absolute position depending on the source of the differential corrections making relocation of the target more difficult. If a common offset in position is detected during target ground-truthing or during subsequent geophysical survey work then this may be the cause.

3.9.3.3 Despiking

Despiking is the term used for the removal of 'spikes' in the dataset - a spike is a measurement that does not fit the trend of previous and subsequent measurements. Zero or failed measurements caused by data dropout can be considered spikes and should be treated in the same way. The measurement associated with the spike needs to be removed and this can be done by removing the measurement completely, setting the value to zero or some number that indicates an error (like -1.0) or by estimating a better value by interpolation. If the despiked dataset is to be subsequently filtered then it is recommended that the value is set by interpolation as many filter algorithms need regularly spaced data which does not contain zero values.

What constitutes a spike is hard to define at low SNR values or where measurements are collected at a low update rate. With noisy data and small targets it may not be possible to clearly distinguish between a spike created by interference and one created by the target itself. A magnetic target that is small in physical size may only show up as a single positive or negative peak in the data if the sample rate is low as is often the case with proton magnetometers, as shown above in Figure 46 plot D.

3.9.3.4 Contamination removal

When operating in harbours the dataset may be contaminated with the effects of passing ships, navigation buoys in the survey area or from known targets. The location of navigation buoys and the time of passing of ships should be recorded in the survey log so the contaminated sections of the dataset can be flagged as bad or simply removed. The information about these unwanted events must be included in the information that accompanies the raw data so others reprocessing the data at a later date do not interpret the anomaly from a navigation buoy as a significant target.

3.9.3.5 Noise reduction

The removal of regional and diurnal effects is described above in Section 3.9.2. The despiked and corrected dataset will still contain noise but it will tend to include higher frequency components such as instrument self-noise. Instrument noise that is a significantly higher frequency than the target signals can be reduced by passing the data through a low pass filter. The low pass filter smoothes out small variations in the dataset leaving the lower frequencies intact and this form of filtering will also reduce any remaining high frequency components of diurnal variation. An unwanted side-effect of high pass filtering is to remove the sharp peaks associated with small discrete targets so estimation of target mass from peak deflection should be done using data that has not been heavily filtered.

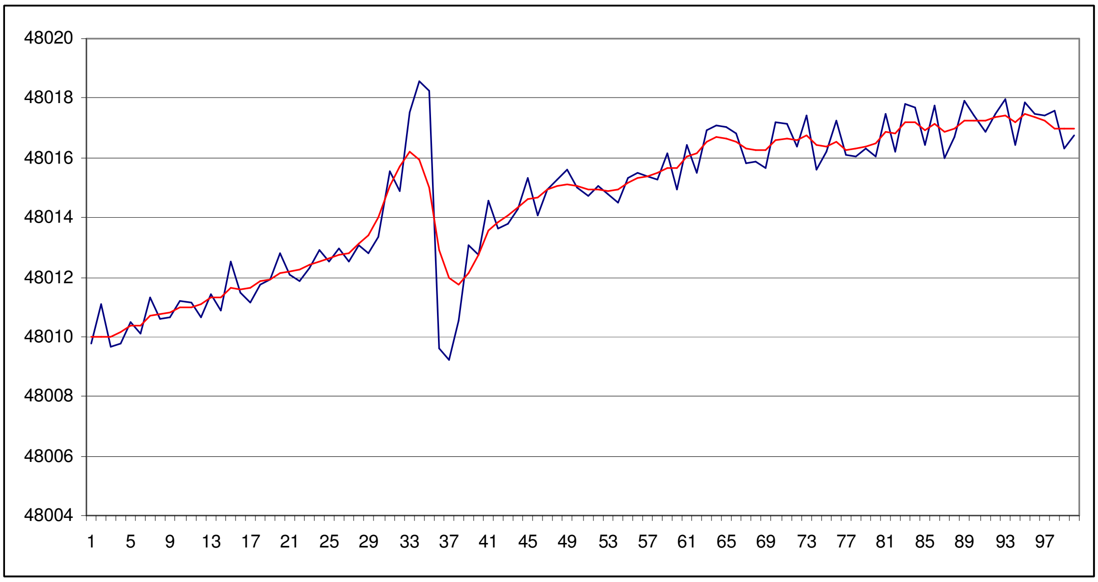

Fig 50 Low Pass Filter

In Figure 50 above the original noisy signal shown on the blue trace has been low pass filtered and the result is shown as the red trace. Note that the filtering process has removed some of the high frequency components of the wanted signal and has lowered the peak to peak amplitude of the anomaly.

3.9.3.6 Spatial filtering

Data filters that operate on the one-dimensional set of measurements have only the measurements before and after in sequence to include in the processing. Where the positions of measurements are well known it is possible to use spatial relationships between measurements to perform 2D spatial filtering so measurements from adjacent lines are also used in the filter. The data from adjacent lines can be levelled to smooth out mean differences as an alternative to normalising data to reduce the measurements to a zero mean. In effect, entire lines are shifted up or down so that they fit better alongside the adjacent lines removing the corrugation effect often seen in data collected with lines run in opposite directions.

More complex spatial filtering is possible and is often used in terrestrial archaeology to aid interpretation. This form of filtering is only possible if the precision of the position estimates is smaller than the spatial dimensions of the filter and if the data density is fairly uniform in all directions. Unfortunately, data collected from marine surveys often has measurement positions with insufficient precision and data densities much higher along track (based on sample rate) than across track (based on runline spacing). This makes spatial filters unsuitable for the majority of marine magnetic survey work.

3.9.3.7 Interpretation

Having computed good position estimates for the measurements and filtered the measurements to remove noise the task of interpreting the data can be done. Interpretation of marine magnetic data to identify targets involves looking for differences in the dataset that have characteristics that we would expect to be shown by the targets we are looking for. A number of factors complicate the task:

The size of target to be found affects the difficulty of the task as it is relatively easy to detect big steel shipwrecks, much harder to detect scatters of cannons and harder still to detect the lone anchor that may signify the location of a shipwreck site.

The depth of water to be searched adds complexity to the task. The short-range detection capability of a magnetometer means that the sensor must be placed close to the target for it to be detected. In shallow water a towfish can be deployed close to the seabed with some confidence in its position. But as water depth increases the amount of layback increases so the position of the fish becomes more uncertain. Solving the positioning problem using a USBL tracking system is often not possible due to budget limitations.

The environment in which the work is done has an impact. Surveying a geologically non-magnetic area is simpler as is surveying an area free of modern iron debris.

Experience provides the clues to finding suitable targets in different environments, particularly when differentiating a geological feature from a cultural one. Much can be gained from comparing data from different parts of the survey area, looking for anomalies that are different from the norm 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 mostly wooden shipwreck.

To be able to interpret the data we need to be able to view it in a recognisable form. The most common way of rendering serial magnetometer measurements is as a time-series plot with the measurement value on the Y axis and time (or distance) on the X axis (see Section 3.9.6.2). Characteristic signatures of anomalies can be identified so long as the SNR is high enough and each separate anomaly can be identified as a target. The target size (in nT) and position should be noted for each along with a description of the signature, better still capture an image of each anomaly as shown on the time-series plot. If the altitude of the towfish above the seabed is known then an estimate of the minimum mass of the target can be calculated, see Section 3.5.2.

Another common method for rendering the data is in the form of a two dimensional map or plan. This shows the magnetic field measurements as a series of symbols so the motion of the towfish is shown as track lines on the plan where colour or symbol size is often used to denote field strength.

One of the main products of this work is a simple list that includes target name, position estimate, target size (in nT) and target minimum mass. If any anomaly in the data has a known cause then a note about this should be included, such as a passing boat or a navigation buoy within the survey area. Along with this list should be provided metadata describing the work done, significant factors about the survey such as layback and a description any processing applied to the dataset.

3.9.3.8 Advanced processing

For the majority of marine magnetic surveys undertaken for archaeological purposes the scope of processing is limited to the detection of targets based on identification of anomalies. Extending this further, target mass estimation from anomaly size was covered in Section 3.5.2 above but the depth of the target can also be estimated using Euler deconvolution (El Dawi *et al* 2004). Most often used for geological prospection, depth estimation has limited use when prospecting for cultural material as the targets are most often on the seabed or only partially buried. Depth estimation of buried targets is possible but only if the signal to noise ratio is high for the anomaly as the ability to estimate depth accurately degrades as the noise level increases.

Euler deconvolution can also be used to assist in automatic detection of targets. Dipole-like targets typical of the ferrous objects searched for in archaeological prospection have a characteristic shape as the field produced decreases with inverse distance cubed. It is possible to identify potential targets by assessing the anomaly shape and identifying which show this behaviour using the extended Euler deconvolution technique (Davis *et al* 2005) or by using wavelets (Billings and Herrmann 2003).

Interpretation can be simplified by making the anomalies the same shape for targets at different latitudes. Magnetic data usually displays plus-minus anomalies which are due to the dipolar nature of the magnetic sources and the interaction with the Earth's field. These anomalies may be converted into positive-only values as if the observations were made at the Earth's magnetic pole and if the magnetization of the buried body was purely induced, this method is known as reduction to the pole (RTP) (Li and Oldenburg 2001).

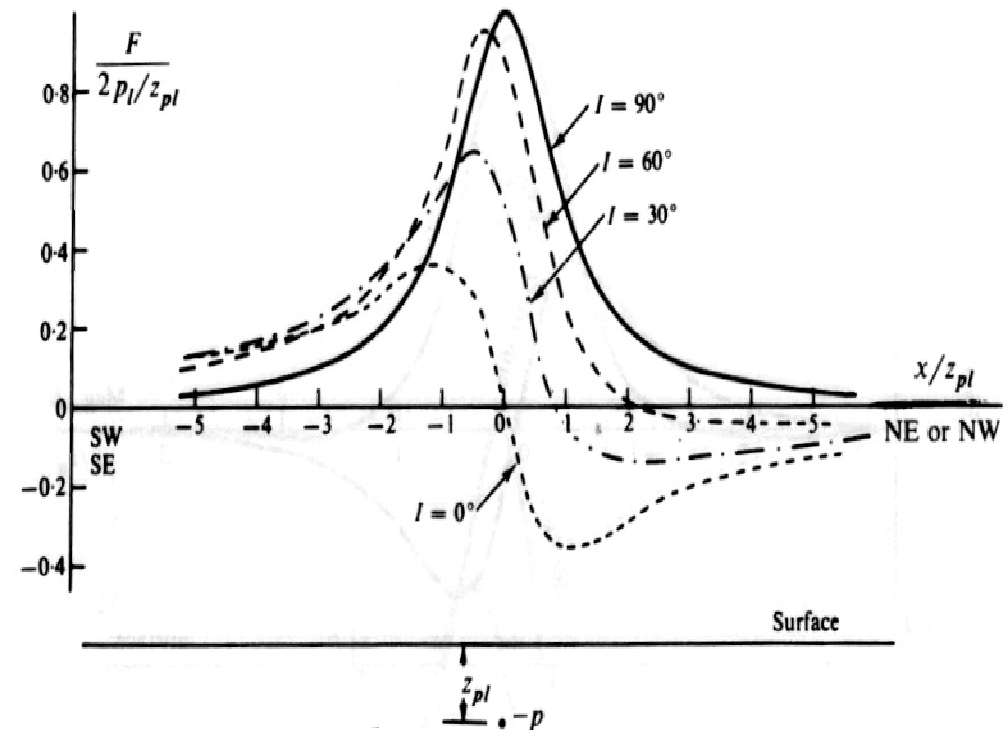

Fig 51 The anomaly shape generated by the same target at different latitudes

The altitude above the seabed and thus the sensor to target distance may vary considerably for survey areas with uneven topology where the towfish depth was kept constant. In this case the anomaly generated by two targets of the same mass in different depths of water would be of different sizes with the shallow water target giving a larger response. A simple 2D plot of field strength would make the shallower target more significant when in fact it was simply closer to the sensor. To compensate for this problem the data can be draped onto a terrain model of the seabed, this transforms the anomalies so that they represent the response that would be measured if the sensor were on the seabed or some fixed distance above it. Drape correction involves projection of the field onto a surface with constant terrain clearance whilst preserving the full bandwidth of the data; this is known as downward continuation and is described in detail in Phillips (1996). The drawback with this method is that downward continuation enhances higher frequency components so enhances high frequency noise, this limits its usefulness to datasets with a low noise content.

3.9.4 Position refinement of total field data

The equation first outlined by Hall (1966) is usually used to estimate target mass from magnetometer deflections. This equation can however also be used to improve target position estimations when the same target is detected on two or more adjacent run lines.

The equation as quoted is:

$$\Delta M = 10^4 \cdot \frac{A}{B} \cdot \frac{W}{D^3}$$

Where

ΔM is the field intensity change in nT

$\frac{A}{B}$ is the length to width ratio of the target

W is the weight of the object (tonnes)

Note – The dipole approximation equation discussed in Section 3.5.2 above can be used in place of the Hall equation.

3.9.4.1 The theory of the method

First we have to assume that anomalies on adjacent run lines were caused by the same target. If we consider the two anomalies and imagine a line drawn on the seabed from the position of the smaller of the two anomalies through (and beyond) the position of the larger of the two anomalies, then the actual target will lie somewhere on this line. To calculate its position we have to find the point on this line where the hall equation predicts the same mass for the target from both magnetic readings. In practice this is achieved by using an iterative procedure which considers points at small intervals along the line, calculates the slant range from the magnetometer positions and then derives the estimated mass for each of these points using the Hall equation. The process ends when two very similar mass predictions are derived for that point on the line. If no solution is found by the time the line has been extended well beyond the position of the larger reading then the anomalies were not produced by the same target.

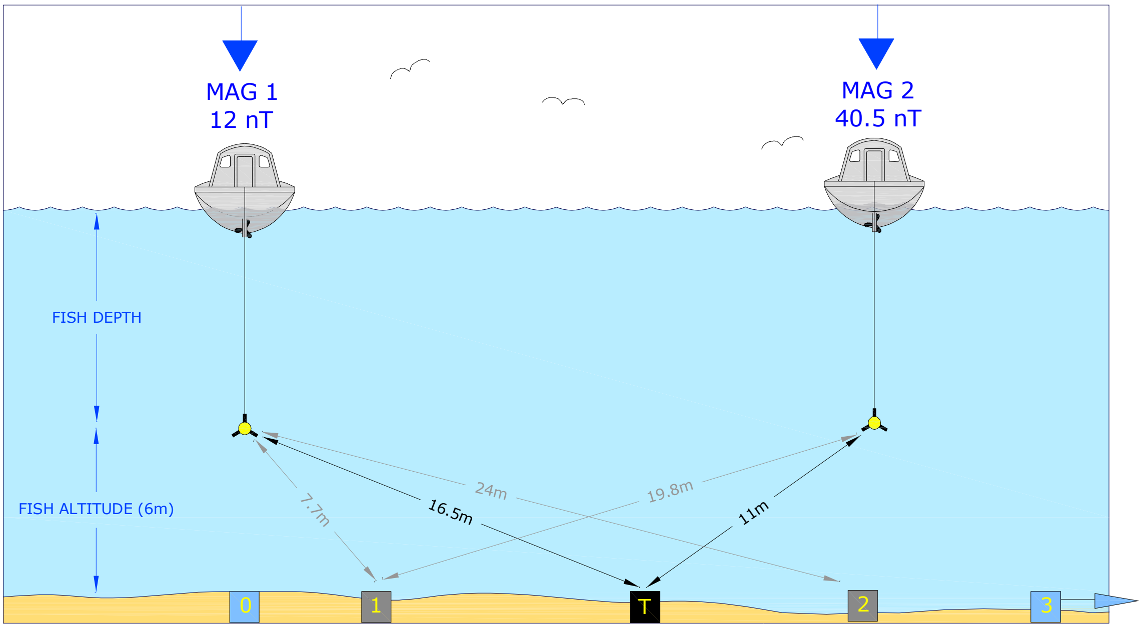

Fig 52 Illustration of the method used to estimate target position where the same target was detected on two adjacent run lines

	Predicted mass	
Seabed location	MAG 1 (12 nT)	MAG 2 (40.5 nT)
[1]	547 kg	31437 kg
[2]	16588 kg	1164 kg
[T]	5390 kg	5390 kg

Fig 53 Table showing mass predictions for the seabed targets shown above in Figure 52

Figures 52 and 53 above demonstrate the method for a number of locations on the seabed between two magnetometer readings, MAG 1 and MAG 2. It will be seen that the mass predictions made from MAG 1 and MAG 2 are the same for point [T] on the seabed – the position of point [T] becomes the estimated target position.

3.9.4.2 The practical application of the method

The calculations can be performed on a programmable calculator or as a VB macro in Microsoft Excel. The data required are as follows:

Total deflection of reading 1 (smaller of the two) in nT

Total deflection of reading 2 (larger of the two) in nT

Fish altitude for reading 1 and 2

Position of reading 1 (preferably in UTM)

Position of reading 2 (preferably in UTM)

First the magnetic anomalies or targets are selected, this is most conveniently done by looking at the data in time series plots – this is where the field strength is plotted on the Y axis against time or position on the X axis. From this the absolute magnitude of the anomaly and its geographic position can be derived. It should be noted that the position of this anomaly is only the closest approach of the magnetometer to the target and not the targets actual position (unless by chance the magnetometer passed directly over the target). The position of these anomalies should then be plotted onto a base map of the survey area – this is usually done in a GIS system. Anomalies on adjacent run lines which may have been caused by a single target can then be selected.

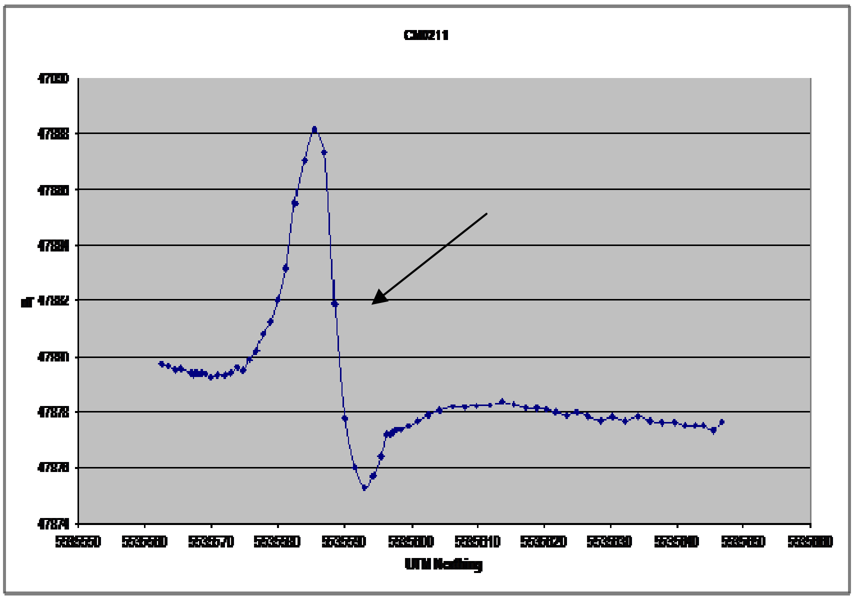

Fig 54 An example of a series plot from the 2005 Colossus Debris Field Survey. The magnetic field strength has been plotted against the UTM northings – the survey lines were essentially north-south. This shows a dipole target of 13 nT total deflection. The arrow shows the data point chosen to take the anomaly's position from

Once this has been done the data can be input to the position estimating algorithm. The result is a position estimate for the target (or a message that no solution was found, indicating that the anomalies were not caused by the same target).

This method has been tried on a number of magnetic surveys conducted by CISMAS. Several examples from the Colossus Debris Field Survey (Camidge and Witheridge 2005) were worked and each produced a solution, these targets were all subsequently recorded by divers and their positions plotted. The predicted target positions varied from the plotted positions by from 1.5m to 3m. It should be noted that the divers positioned the targets using a distance measurement and a compass bearing taken on the seabed relative to a shot line positioned using ordinary EGNOS-enabled GPS.

Another example where the method was used was on the CISMAS survey of Mount's Bay (Camidge and Randall 2009). A very good magnetic target which showed on two run lines produced no anomaly at all on the side scan sonar. A prediction of target position using the above method was made and that position was investigated by divers. Nothing was found on the seabed at that position, but a strong, clearly defined metal detector target indicated the presence of a buried iron object.

Example 1

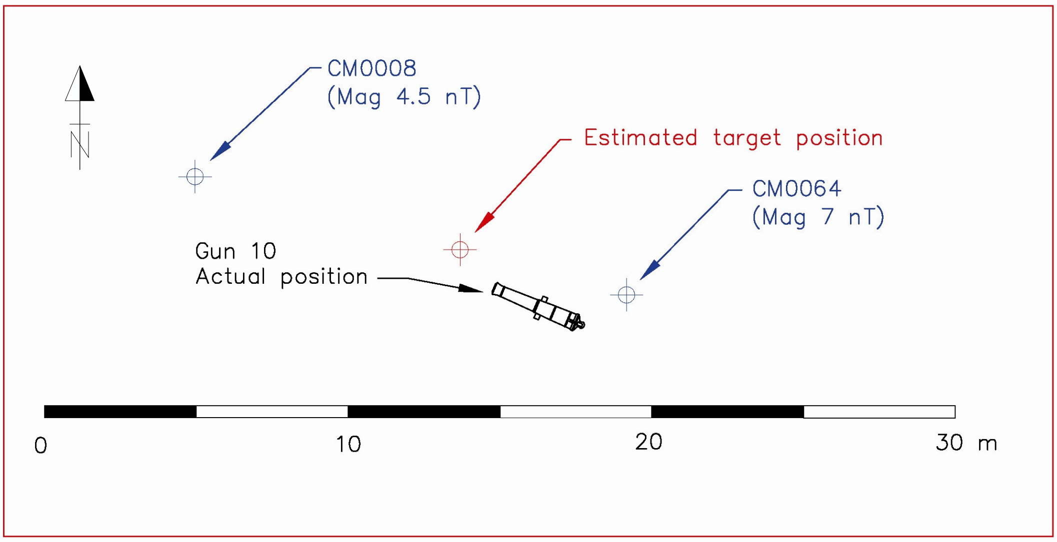

Fig 55 An example of target position estimation using data from two adjacent run lines

The above example (Figure 55) is taken from the *Colossus* Debris Field Survey (Camidge and Witheridge 2005). The target in question proved to be a 32lb Blomefield pattern iron gun, 2.95m long with an original weight of 55cwt (2.75 tonnes). The estimated position is some 1.7m from the muzzle of the gun.

Example 2

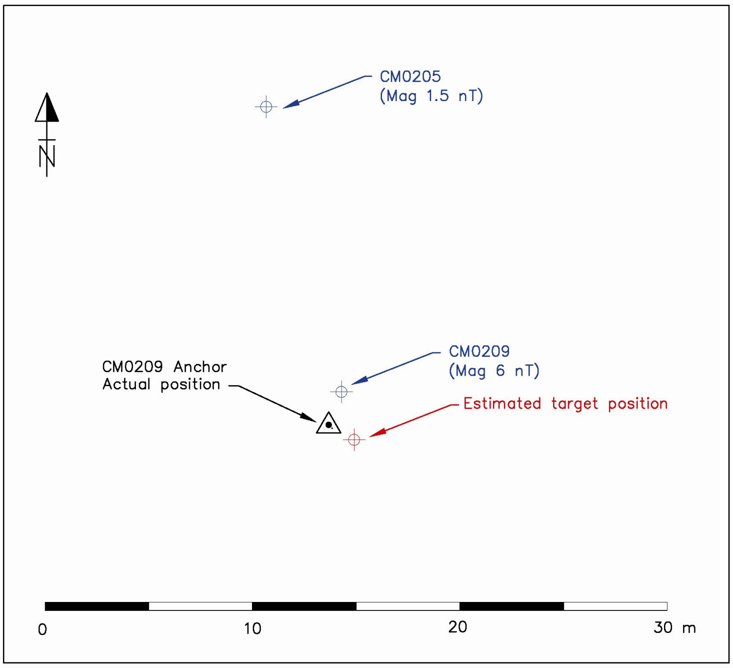

Fig 56 An iron anchor found on the Colossus Debris Field Survey (2005). The arms of the anchor were buried below the seabed, exposed shank > 1.85m in length.

The estimated target position is 1.5m from the anchor shank.

The method is useful in refining magnetic target position where no corresponding side scan sonar data is available to give a more accurate position. This can occur where the object is buried below the seabed or where side scan sonar was not deployed as part of the survey. The method is of particular use where divers are to be deployed to record the object as it can cut down the time spent searching for the target – this can be considerable in poor visibility or where kelp growth obscures targets.

As an alternative to the iterative solution outlined here a closed equation can also be used, as demonstrated in above in Section 3.5.2.

3.9.5 Methods of representing target data

3.9.5.1 Introduction

There are several principal means of representing magnetometer data for dissemination in survey reports, each with their own benefits and drawbacks. These methods range from simple two-dimensional graphs to three-dimensional surface models and serve to communicate different information about the survey data. In this section the advantages and applications of these different methods of representation are considered and illustrated using an archaeological dataset.

3.9.5.2 Time series plot

The time-series plot is a graph where field strength is plotted on the vertical Y axis against time or distance on the horizontal X axis. In effect these graphs represent a section through the magnetic field. The size and shape of the field is clearly shown allowing for ready interpretation and as such this method of visualisation is often used when analysing magnetometer data.

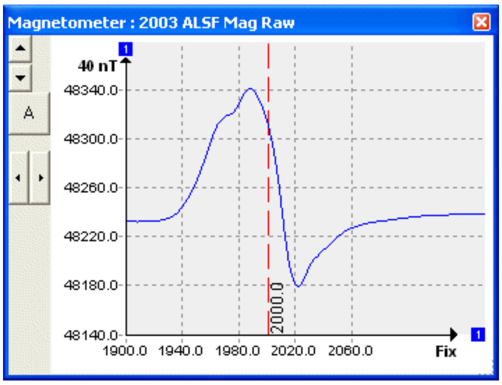

Fig 57 Time-series plot

Shown above in Figure 57 is the magnetic field across the wreck of the *Hazardous Prize* in Bracklesham Bay, the eastern Solent. The deflection of the earth's magnetic field caused by the wreck-site is plainly observable and information such as the amplitude of the deflection can be easily gleaned. This method of representing magnetometer data can be achieved in software such as Microsoft Excel and is very effective at illustrating the properties of individual anomalies.

When attempting to visualise an entire run line, which might contain many anomalies of different scales, time-series plots can prove ineffective. This method also fails to show the spatial relationships between different run lines and anomalies. However, time-series plots can be used to complement simple site plans where the location of individual targets are plotted (see Figure 60 below).

3.9.5.3 Colour-weighted runlines

Much the same information can also be shown using colour-weighted runlines, where the track of the magnetometer is shown in plan view. The range of values for field strength is assigned a range of contrasting colour values and so deflections in the earth's magnetic field are visible.

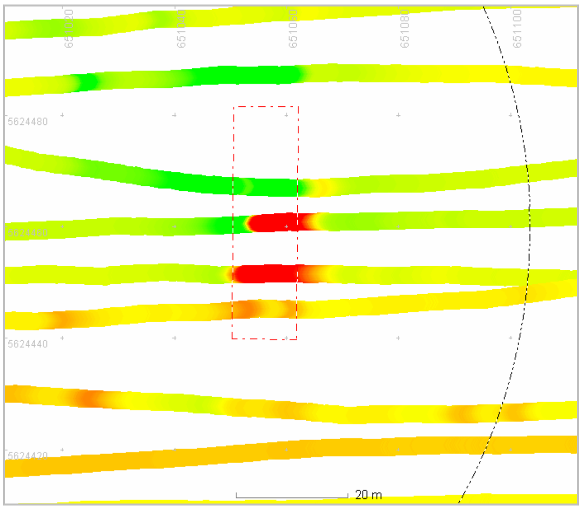

Fig 58 Colour-weighted runlines

In Figure 58 the red areas show regions of increased field strength, the green areas show regions of reduced field strength and the areas which do not deviate significantly from the typical value are shown in yellow. When viewed in this way the relationship can be seen between anomalies detected on multiple runlines or multiple surveys. In Figure 58 we can see the red areas on two different lines suggesting that these correspond to a single target, in this case the anomaly is caused by the main wreck site that includes a number of iron guns and concretion.

The additional information may help during interpretation. Targets identified on other geophysical surveys may correlate with targets on this survey or other features may be identified such as boat moorings or navigation buoys. The shape of the anomaly is more difficult to see in this kind of plot so interpretation may also benefit from the use of time series plots.

As the data is visualised in plan other information such as depth contours, known wreck-sites and the results of previous surveys can also be illustrated, therefore allowing the magnetic data to be viewed in context. Furthermore, if anomalies have been investigated and identified, the results can be indicated using corresponding symbols on the plan as is shown below in Figure 59.

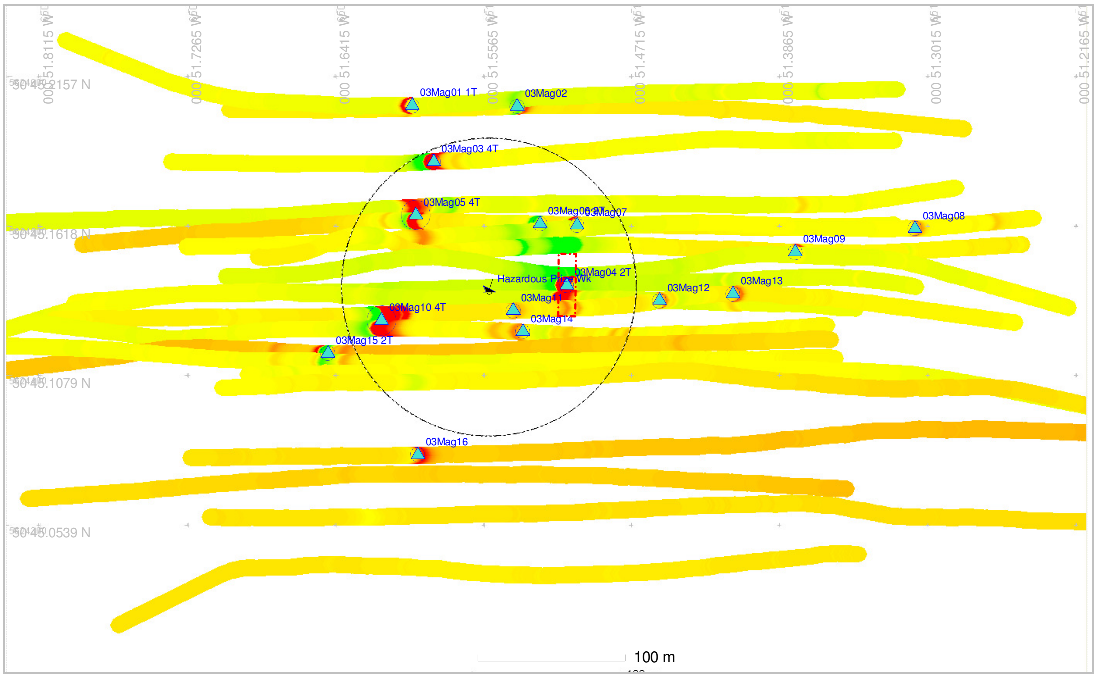

Fig 59 Results indicated by corresponding symbols

Colour weighted run lines unfortunately fail to portray the characteristics of individual targets as efficiently as time series plots. Furthermore, small targets can often be concealed by larger and broader variations in the data-set caused by larger targets or regional and diurnal influences upon the total field.

3.9.5.4 Target plot

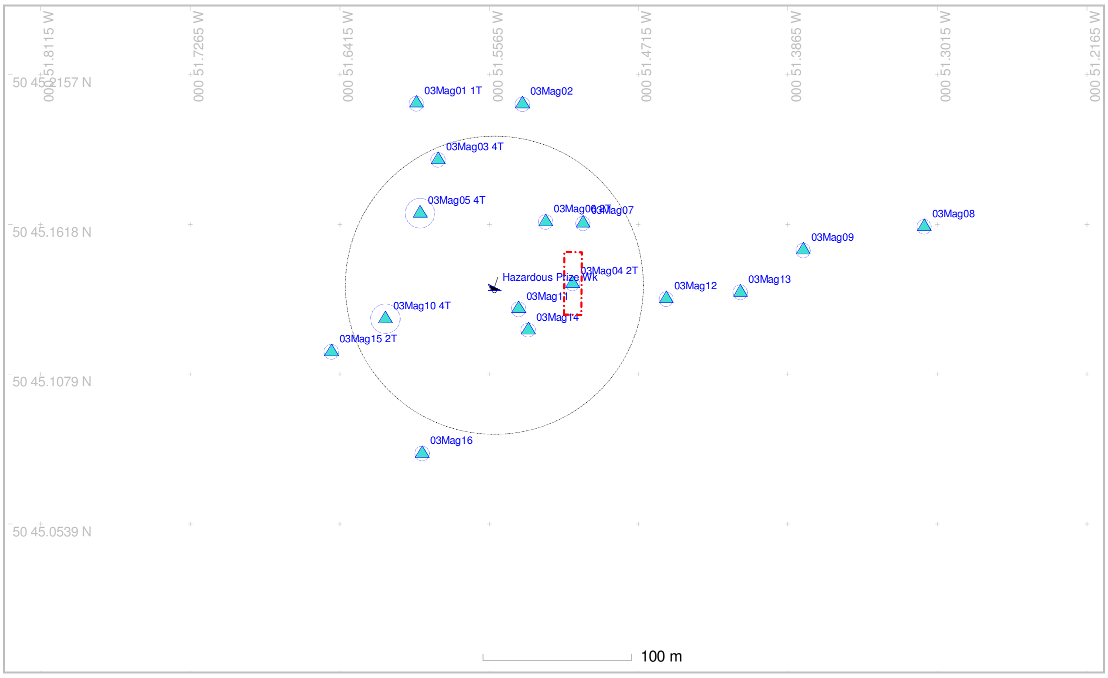

Fig 60 Track plot as a set of points

Although the track lines may be of interest, quite often it is the targets themselves that are of prime importance so simple target plots can be used. The post-processed information in the track plot can be reduced to a set of points on a chart, or further reduced to a list of points, their estimated positions, depths and target mass.

The reduced set of target points can then be investigated in turn, identified and documented. Where the investigation fails to show a source for the magnetic anomaly the raw track plot information may have to be re-examined so it is essential to retain all the raw data from a marine magnetic survey.

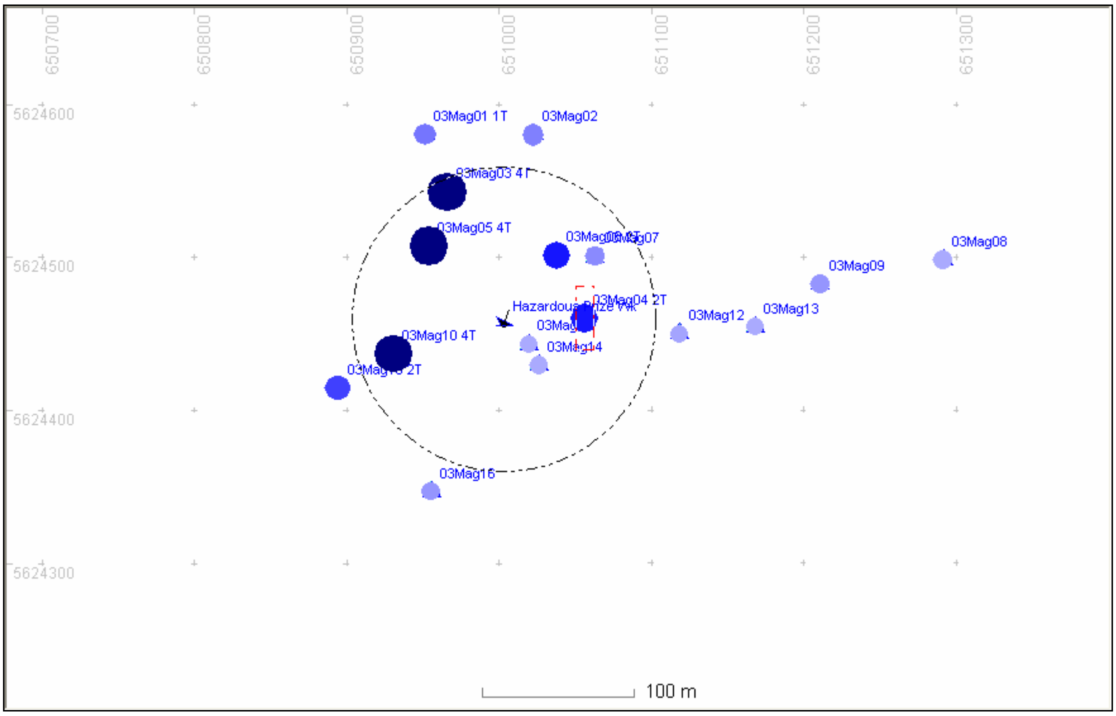

Fig 61 Plan of anomalies where circle diameter indicates estimated mass relative to other anomalies

3.9.5.5 Contour plot

Interpolation of the magnetometer data set can be used to produce a representation of the magnetic field strength over the entire search area. The field strength can then either be illustrated as a contour plot such as in Figure 62, or as colour density map as in Figure 60. Marine survey data is commonly represented in this way as such maps appear easy to interpret and look good in published reports. Enright *et al* (2006) recommend the use of contour plots for the visualisation and interpretation of data as an anomaly's width and polarity can then be easily derived. Such characteristics can be used to discriminate between shipwrecks and items of debris (Enright *et al* 2006).

Large anomalies can overwhelm smaller anomalies making them difficult to identify on contour plots. Plotting the logarithm value of the field rather than the raw field can help as it compresses the higher values and accentuates the smaller variations.

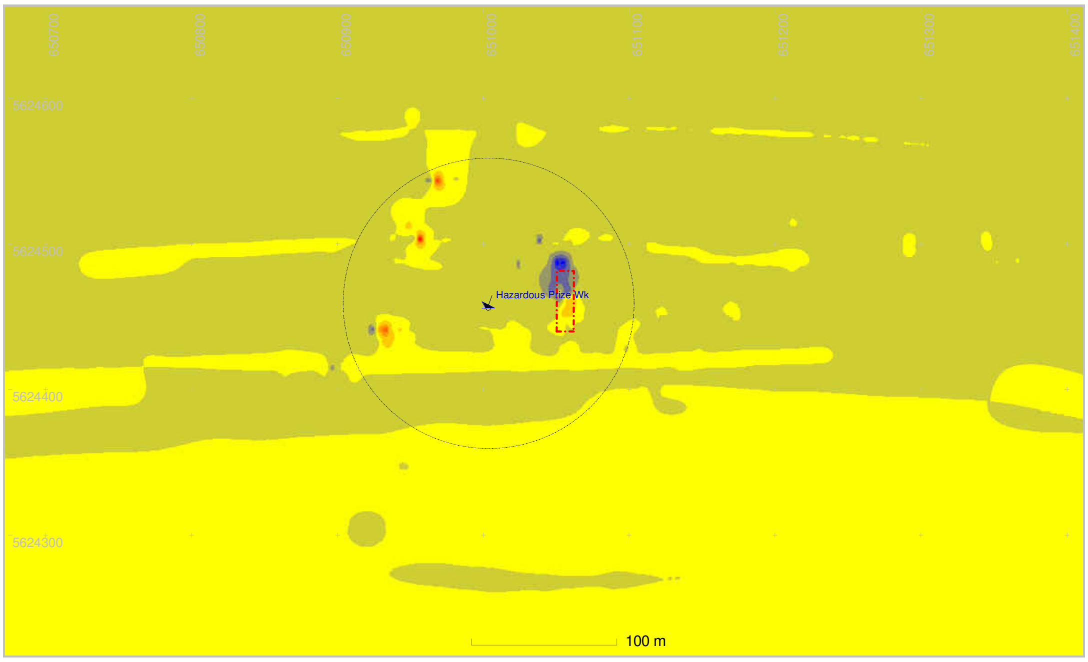

Fig 62 Contour plot

This kind of plot can also make the data appear to be of far higher quality than it is. The data used to create the contour plot may have a high data density along each track but between tracks there is no data. As the process of interpolation automatically fills in the spaces between lines it suggests that the data density is the same in each direction when in fact the track plot (Fig 58) shows large gaps between some lines where additional targets may lie. Also, parallel survey lines that identify adjacent anomalies will often be shown on a contour or colour density map as a single, dispersed anomaly.

The uncertainty in position for the towfish and background noise will affect the validity of contour plots as most contouring algorithms cannot account for these errors. The effect is that the detail in a contour plot may not be caused by subtle variations in the magnetic field caused by wreck remains but may actually be caused by the more mundane effect of inaccuracy in the towfish position or a high signal to noise ratio.

These methods of representation are useful for showing wide area magnetic effects. As such they can be used with success on large wrecks where dislocated sections and dispersed areas of debris occur. However, similarly to colour weighted run lines, they often fail to illustrate any significant information about individual anomalies and small targets can be masked by larger ones.

3.9.5.6 3D surface models

3D surface models are an extension of contour plots. Once the data has been interpolated it can also be visualised in three dimensions, often with a colour density map draped over the top. 3D surface models provide information about the size and shape of individual anomalies, though to a less effective extent than time series plots.

Contour plots, colour density maps and 3D surface models all rely upon interpolation and as such suggest a higher density of data then has actually been achieved. Their use in archaeological reports is often striking however it should be made clear that they represent an interpretation of the dataset.

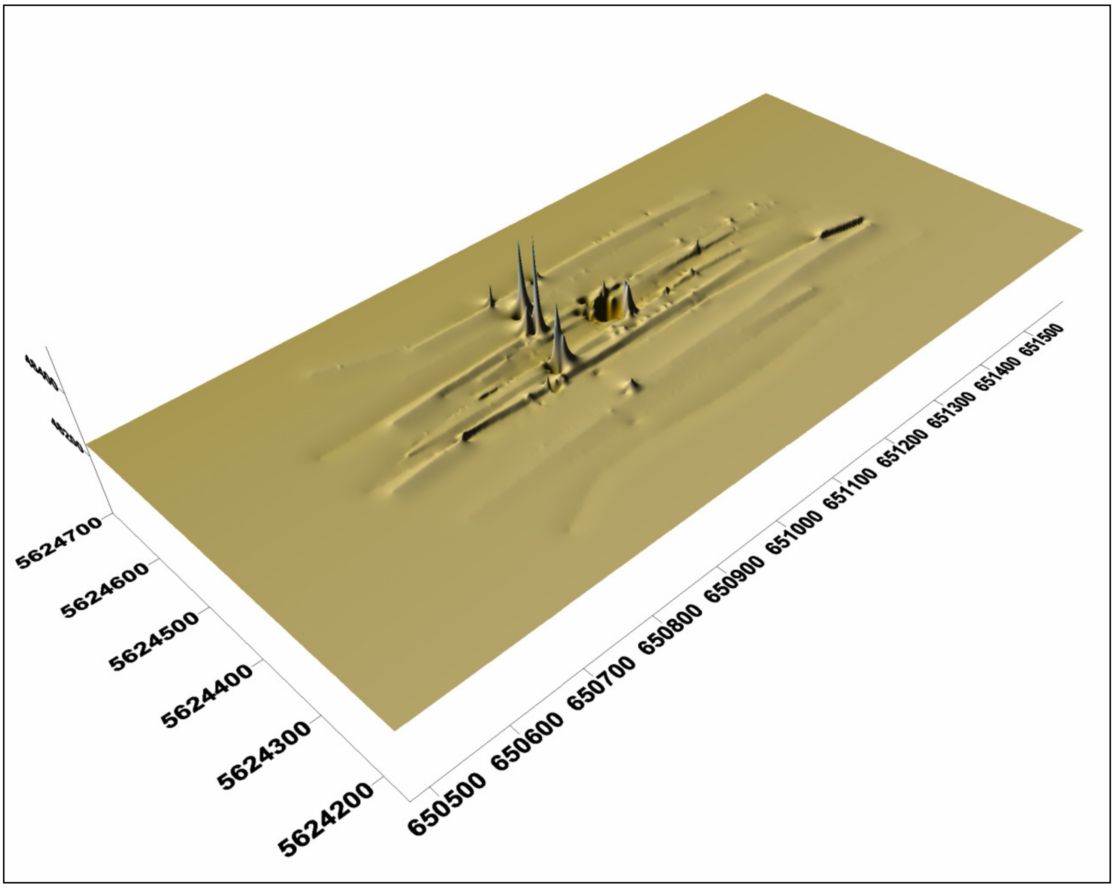

Fig 63 3D surface plot

3.9.5.7 Conclusions

It is apparent that the principal methods of representing magnetometer data for publication can be divided into two categories. Some methods are suitable for communicating the characteristics of individual targets, whereas others communicate information about the survey area and dataset as a whole. It is important to consider which of these two purposes a particular illustration is to serve and to select the relevant method accordingly.

Contour plots and 3D models are best avoided unless the data density is high in all directions, the signal to noise level is high, the survey area is free of clutter and the anomalies being shown appear on more than one survey line.

3.10 Publication and archiving

3.10.1 Publication

A marine magnetometer survey often forms just one part of a larger geophysical site investigation and the magnetometry results will often be published as part of a combined survey report. The results of marine magnetometer surveys are often interpreted and disseminated in 'grey literature' reports so access to the data is sometimes rather limited. Where the survey work has been commissioned by one organisation but undertaken by a sub-contractor it can often be difficult to get access to the raw survey results.

Published reports can contain a synthesis or section on geophysical survey results as appropriate, with the technical report being deposited with the archive and referenced in the publication. A synthesis of the work is sufficient for an overview but a detailed publication or the raw data is preferred if the survey work is to be extended or repeated. Any survey data is open to re-interpretation as the process is somewhat subjective so publication and archiving should be done with this in mind.

The ways in which the information can be represented in publications is discussed in Section 3.9.5 above.

3.10.2 Archiving

Geophysical survey data forms part of the documentary archive for any site so should be archived with the same care and attention given to other elements of that archive. The data may have been expensive to collect and process and may capture the 'state' of the site at one fleeting moment that cannot be repeated. The data is also a valuable source of information for anyone continuing work on the site so the archiving policy should include access to the raw information from the survey.

Any processing of raw magnetometer data will involve some form of filtering and the results will have some information removed. A different form of processing or filtering will produce a different set of results. The processing applied to the data will depend on the types of targets to be identified, the processing tools available to the operator and to some extent the operator's skill. Therefore there is always room for improvement in any processed dataset as requirements and techniques develop. Therefore it is essential to include in the archive raw logged magnetometer data that has not been altered by despiking, levelling, filtering or any other subjective and often non-reversible process.

As well as the raw data it is essential that the metadata is included as well - other information that describes how the magnetometer data was collected, when, using what equipment and so on. The metadata should provide sufficient information for someone else to be able to reprocess the data in the same way as the originators and to get the same results, or to reprocess using different methods.

The archive should also include the final processed version of the dataset to give other users the option of reusing the processed results alone. Interim versions and experimental processed versions should not be included in the archive unless accompanied by detailed descriptions and metadata that define what they are and why they were important enough to include in the archive.

The raw data should be archived digitally in a simple, easily read text format such as Comma Separated Variable (CSV), a format that can be read and displayed by most spreadsheet programs and text editors that can easily be ported between platforms. The problems often associated with archiving geophysical data affect magnetometer data far less than other geophysical instruments as the effective data rate is much less, around 10 kilobytes per minute.

There is currently no suitable provision for the archiving of digital marine geophysical data but a number of projects are now in progress to review procedures and guidelines for marine digital datasets and maritime archives in general. A comprehensive and detailed guide to best practice in creation, compilation, transfer and curation of archives can be found in Archaeological Archives by the Archaeological Archives Forum (Brown 2007).

3.10.3 Current projects reviewing maritime archives

3.10.3.1 Archaeology Data Service

The Archaeology Data Service's 'Geophysical Data in Archaeology: Guide to Good Practice' was compiled in *c*1998 (Schmidt nd). Although it is now outdated it provides some useful advice on issues such as metadata etc

(http://ads.ahds.ac.uk/project/goodguides/geophys/).

Their guides for the creation and archive of geophysical datasets (terrestrial and marine) are currently undergoing a major revision which is partly EH funded and using some of their case studies (T Evans pers comm). The main output will be ready in 2010 and could be assimilated into the final report of the 'Developing Magnetometer Techniques to Identify Submerged Sites' project if there are phase 2 field trials are commissioned for 2010-11.

Another ADS project: the VENUS (Virtual ExploratioN of Underwater Sites) project, informs their revision of the guides and has stand alone project outcomes and recommendations for marine geophysics, but excludes magnetometry. The results have recently been presented online.

3.10.3.2 Maritime and Marine Historic Environment Research Framework for England

The Centre for Maritime Archaeology at the University of Southampton have been commissioned by English Heritage to co-ordinate the development of a research framework for the maritime, marine and coastal archaeology of England.

http://www.southampton.ac.uk/archaeology/research/projects/maritime_research_framework.html

The research framework will provide a coherent overview of previous research into the maritime and marine historic environment of England, which will enable long-term strategic planning, inform policy and provide a statement of agreed research priorities within which researchers can shape and seek funding for projects.

In order for this to be both a successful reflection of the current state of knowledge and a vehicle by which the key research questions for this diverse community can be identified, it seeks to engage all those involved in the maritime, marine or coastal archaeology of England, from the academic, commercial and voluntary sectors, in its creation. The project has a working group on archaeological archives and collections and introductory seminars and a working group workshop were held in June and July 2009. A larger project conference will be held in April 2010, to present the Resource Assessment and agree the Research Agenda.

3.10.3.3 Institute for Archaeologists

The IfA's Geophysics Special Interest Group (GeoSIG) have set up a number of working groups commissioned to study aspects of current practice, including current and future archival strategies. The first AGM of the GeoSIG, in 2008, agreed the need to form a working group to address the issues of archiving data in geophysics, a detailed questionnaire has been prepared to better understand the present situation and collect proposals before an attempt can be made to describe current practice or propose future strategies, the present situation

needs to be better understood and proposals collected and to do this a detailed questionnaire has been prepared
http://www.archaeologists.net/modules/news/article.php?storyid=380

3.10.3.4 Securing a Future for Maritime Archaeological Archives

The situation in the UK relating to maritime archaeological archives and collections has recently been investigated through the 'Securing a Future for Maritime Archaeological Archives' project being carried out by the Hampshire and Wight Trust for Maritime Archaeology (HTWMA) with the IfA and ADS for English Heritage, Historic Scotland, the Royal Commission for the Ancient and Historic Monuments of Scotland and the Society of Museum Archaeologists.

The project gathered data in three key areas to establish:

- Current geographical remits of museums and archives in the offshore zone
- The extent of the current situation regarding maritime archives
- Gauge future demand for maritime archaeological archive capacity.

The results have provided baseline data which can be used by agencies, organisations and institutions to assess the most appropriate way to deliver increased support for those creating and curating archaeological archives. It will also help inform the development of future archive management capacity on a national level to ensure important collections have a publicly accessible home and are properly curated for current and future generations of researchers, school children and members of the public interested in their maritime heritage.

3.10.3.5 EH Guidance

English Heritage's Management of Research Projects in the Historic Environment: MoRPHE Planning Note 1 Marine Archaeological Geophysical Survey (2006) is now slightly out of date. It acknowledges that although information on 'new' seabed anomalies contained within 'grey literature' may ultimately be provided to the NMR, there is currently no suitable provision for the archiving of digital marine geophysical data and although English Heritage are addressing this and they currently recommend that the digital archive is maintained for five years following completion of the project. They recommend that an OASIS record is completed and that consideration should be given to the provision of metadata to the Integrated Coastal Hydrography (ICH) Partnership. The latter project was collaboration between the Environment Agency, the Maritime and Coastguard Agency, Ordnance Survey and the United Kingdom Hydrographic Office (UKHO) focusing on improving the quality and availability of bathymetric data in the shallow water areas which came to an end in 2006. The project had three main objectives.

A web enabled database of survey metadata

A definitive specification for gathering bathymetric data in shallow water areas.

A report on emerging technologies for gathering shallow water data (ICH 2004).

3.10.3.6 Marine Environmental Data and information Network (MEDIN)

From April 1 2008 the Marine Environmental Data Action Group (MEDAG) and the Marine Data Information Partnership (MDIP) merged to form a single organisation, the Marine Environmental Data and Information Network (MEDIN). The focus of activities continued to be to improve access to and management of UK marine environmental data and information for the benefit of the whole marine community.

MEDIN has unified funding arrangements, and NERC (the Natural Environment Research Council) continue to provide administrative support and office support for MEDIN staff at the British Oceanographic Data Centre in Liverpool.

The existing pilot network of interlinked Marine Data Archive Centres, working to agreed standards of best practice, will be expanded and enhanced to provide secure long-term storage for an expanding range of marine data sets. The network will provide the capability to upload and retrieve data – which will always be available to the data owners.

A full range of standards are required to allow users to locate and assess the marine datasets they need, to provide guidelines for the generation and preparation of data according to recognised standards and best practice, and to help partners meet their obligations under the INSPIRE directive. The standards will be developed in coordination with related programmes.

MEDIN will coordinate the UK input to the development of international data commitments and drivers that may influence marine data management in the UK (eg INSPIRE, WISE, IOC and ICES Data Policies).

4 Recommendations

The recommendations arising from this report will be incorporated in the forthcoming guidance notes on marine geophysics by Dr Justin Dix.

4.1 Recommendations for magnetic surveys

1. When collecting marine magnetometer data for the purposes of archaeological assessment, it is recommended that a runline spacing of 15m and towfish altitude of 6m be used, thus any target with a mass greater than 450kg should be detected on at least one runline. Where targets of a considerably larger mass are the subject of the survey, the runline spacing and towfish altitude can be adjusted accordingly (Section 3.6.1). It is important that the limitations of a data set or survey methodology are understood and clearly stated in the report – which should in any case state the likely minimum mass of iron which can theoretically be detected by the survey, and thus what will not be detected by the survey.
2. To reduce inconsistencies in towfish altitude runlines should oriented with the local seabed topography (Section 3.8). Cross-lines should be completed at a minimum of 5 times runline spacing (Section 3.8.5).
3. In order to ensure sufficient density of data, it is recommended that a minimum sample rate of 4Hz be used at a survey vessel speed of 4 knots (Section 3.4.2).
4. It is recommended that surveys be conducted in calm sea condition in order to minimise the impact of swell noise upon the magnetometer data (Section 3.9.1.7).
5. It is advised that RTK GPS be employed to fix the position of the survey vessel. Where the survey is operating in an area not served by GPRS reception, Differential GPS should be used (Section 3.7.2). In water depths greater than 20m and where the possible the towfish position relative to the survey vessel should be determined using an Acoustic Positioning System (APS), this is of particular importance where the towfish is deployed a significant distance behind the survey vessel (Section 3.7.7).
6. Where budget constraints preclude the use of an APS, layback calculations should be tested using a known anomaly and runlines of opposing headings (Section 3.7.4) to

quantify any along track layback errors – this check should be a standard set up test along with checking the towfish altitude sensor by direct measurement.

7. It is strongly advised that surveys be completed using an instrument fitted with a sonar altimeter (Section 3.6.1).
8. It is recommended that traditional proton precession magnetometers should no longer be used in marine archaeological surveys, except where the expected target mass is relatively large or budget constraints preclude other types of instrument.
9. A survey log should be maintained during all marine magnetometer surveys. Events such as the towfish passing close to moored or mobile vessels, mooring buoys or other magnetic objects should be logged along with time and runline; therefore negating the misinterpretation of such anomalies within the survey data. Other factors or events which are likely to impact upon the resolution of the magnetometer or positional data, such as sea state and GPS drop-outs, should also be logged.
10. Survey data should be maintained and distributed as ASCII text files, with separate files for individual runlines. Each file should include columns of data for raw (ie survey vessel) positions, layback corrected positions, raw (ie unfiltered) magnetic values, time/date stamps and towfish altitude. Where a towfish with a sonar altimeter has not been used, fish depth and survey bathymetry should be included. Where processed (ie filtered) magnetic values are included, this should be in addition to, not in place of, the raw magnetic values.
11. Survey data should be distributed with accompanying metadata and a copy of the survey report. Metadata is to include a clear description of each column of data within the survey files. Where filtered magnetic values are included with the survey data, the processes carried out should be clearly defined (for instance 'cleaning' and 'de-spiking'). The methods of position fixing (ie GPS type) and layback correction, along with the spheroid and datum used, should be described. It is recommended that survey reports should include a full list of targets identified, along with time-series plots for each individual target and survey metadata. Survey data should be included on DVD/CD where possible.
12. In an ideal survey, a small test target slightly larger than the minimum detectable mass that the survey is designed to detect will be deployed at the start of the survey. This will confirm that the survey parameters are suitable to detect the desired objects and that assumptions about noise levels and smallest detectable anomalies are correct. The test target can consist of an iron object tied to a buoy, which is lowered to the seabed and retrieved after the test has been undertaken.
13. Efforts should be made to balance realistic survey practices and the requirements of related geotechnical investigations against the plausible archaeological potential of the area under investigation. To this end, survey resolution should be influenced by location specific documentary research and projects such as Bournemouth Universities *Refining Areas of Maritime Archaeological Potential for Shipwrecks* (AMAP 1).

4.2 Recommendations for further investigation

1. Investigate the accuracy of layback calculation of the towfish position. This could be achieved using an acoustic towfish tracking system in conjunction with an RTK GPS unit. The layback calculation should be checked at different tow cable lengths to determine the amount of error in position of calculated layback correction. There are two types of error which need separate quantification, along track error (which can be checked at the start of each survey) and cross track error, which is harder to quantify.

Different data collection software may give different layback calculations in the same operating conditions – this needs testing under controlled conditions.

2. Investigate the accuracy of towfish altimeters and depth sensors.
3. Construct a table of test target data. This is unlikely to be achieved using existing data as all parameters need to be known accurately (towfish altitude and position, target mass, shape and orientation and slant range from towfish to target). Accurate positioning of the towfish will be needed, using RTK GPS and acoustic tracking of the towfish. The position of the test targets will also need to be established accurately, probably by using an acoustic tracking system. This table of test data can then be used to establish the constant values (bulk density and magnetic susceptibility) for different archaeological targets using the dipole approximation equation. Test targets should be about six in number and include the common archaeological targets, such as a cast iron gun, wrought iron anchor and a piece of steel wreckage. This should lead to better understanding of mass prediction for targets. Savings could possibly be made by undertaking this at the same time as the trials proposed in Recommendation 4.2.2.
4. Investigate data quality, noise levels and signal quality in the three types of magnetometer using the test targets under tightly controlled conditions. This should answer questions such as:
    - Does the Overhauser produce similar data to the Caesium vapour magnetometer?
    - Are there practical advantages for the higher data rates available with Caesium vapour magnetometers? How do the instrument noise levels compare under the same conditions?

Note: even though proton precession magnetometers are not recommended for general archaeological marine magnetic surveys, if resources allow they should be included in the proposed trials for a number of reasons. They are still suitable for use in surveys aimed at larger iron targets (wrecks).There is considerable legacy data existing which was collected using this type of instrument. Understanding how it compares, in practice, with current instruments would be useful and may help with interpretation of legacy data. It would also be helpful to determine whether actual practical results accord with the predicted (theoretical) results.

5. Establish the effects of data rate on sensitivity in the three main types of marine magnetometer (Proton, Overhauser and Caesium vapour). This will be accomplished using the test targets employed to construct the test data targets (above).
6. Determine the effect of increased range on FWHM estimations of slant range.
7. Test the efficacy of the position refinement method outlined in section 3.9.4 under controlled conditions.
8. Collect data under controlled conditions from iron shipwrecks of known size and condition. This should enable evaluation of the differences between wrecks and individual targets outlined in Enright *et al* (2006).
9. The smallest detectable anomaly for each type of instrument needs to be established under controlled conditions. This will need to be determined for each data rate of which the instrument is capable, as data rate may cause changes in sensitivity/noise levels which will in turn affect the smallest detectable anomaly.
10. The claimed advantages for gradiometers make these instruments of interest to those conducting or commissioning marine magnetic surveys. They have not to date been

much used for archaeological surveys. The additional complexity and cost of gradiometers needs to be considered against the potential benefits – this is an area where trials under controlled conditions would be of benefit.

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5.1 Web Sites

5.1.1 Marine magnetometer

http://geometrics.com/

http://www.marinemagnetics.com/

http://www.ixsea.com/en/

http://www.planet-electronics.co.uk/

5.1.2 Diver held magnetometer

http://www.jwfishers.com/divermag1.htm

http://www.quantrosensing.com/

5.1.3 Depressor

http://www.brooke-oceanusa.com/bot-wing.php

http://www.jwfishers.com/ddw.htm

5.1.4 Maritime archives

(http://ads.ahds.ac.uk/project/goodguides/geophys/).

http://www.southampton.ac.uk/archaeology/research/projects/maritime_research_framework.html

http://www.archaeologists.net/modules/news/article.php?storyid=380
'Securing a Future for Maritime Archaeological Archives'

6 Project archive

The HE project number is **2009030**

The project's documentary, photographic and drawn archive is housed at the offices of Historic Environment, Cornwall Council, Kennall Building, Old County Hall, Station Road, Truro, TR1 3AY. The contents of this archive are as listed below:

1. A project file containing site records and notes, project correspondence and administration and copies of documentary/cartographic source material (file no 2009030).

2. This report text is held in digital form as: G:\CAU\HE Projects\Sites\Maritime\Developing Magnetometer Techniques 2009030\Developing Magnetometer Techniques Theoretical Study Final Report

7 Appendix: summary table of literary sources

Reference	Summary	Notes
Abelrahman *et al* 2003	least-squares minimization	
Anderson *et al* (nd)	Comparison of marine magnetometer to aeromagnetic data	
Arnold 1981	Remote sensing in underwater archaeology	
Arnold 1996	Magnetometer survey of La Salle's ship the *Belle*	
Barckhausenn *et al* 2004	A new towed vector marine magnetometer	
El Dawi *et al* 2004	Euler deconvolution	Post processing for target depth estimation (a grown up needs to read this)
Hall 1966	Proton magnetometers in underwater archaeology	Proton precession magnetometers Equation to determine: 1. Deflection 2. Distance Detection of iron and ceramics Lane spacing – theoretical 2x max detectable distance - Best 1x max detectable distance Boat speed – 3 factors anomaly size, fish depth and polarisation/data rate. Detection persistence – number of readings required to detect target. Methods of controlling fish depth Problems of position fixing – fish may not follow boat, suggests sonar positioning of fish. Magnetic hazards – geological mag gradients (nT/m) – geological noise can need altered lane spacing. Fig 7 same target EW & NS only one shown as a dipole.
HES 2004	HMS Scylla Archaeological Assessment (Survey Report)	Proton mag used in conjunction with side scan, multibeam and bottom sampling. 3.2.2.1 – Mag data presented as a single magnetic amplitude graph on printed paper.

Reference	Summary	Notes
		Scale accords to 1:15000 Non georeferenced data so derived positions approximate. Surface tow assumed. Smallest anomally observable = 10nT Between 4 and 10 tonnes 3.2.2.2 – 50m run line spacing. Survey area 500m x 400m. Georefenced plan of survey lines presented in hard copy, based on UTM Zone 30 WGS 84 Spheroid.
HES 2006	South West Wave Hub Archaeological Assessment (Survey Report)	3.5 – Mag and side scan used to identify wrecksites. 6.1.2 – Mag data collected by EGS and provided as xyz files. 6.1.4 – Line spacings of 75 and 100m used. 6.1.5 – MM SeaSpy used. No fish depth provided in data. Max. Assumed fish depth of 3m. Water depths in survey area between 0-60m CD. In deepest part of survey minimal detectable target calculated as between 9 and 40 tonnes. Data evaluated as magnetic amplitude graphs. Anomalies plotted in AutoCAD to highlight any concordances. Tow fish was towed far too shallow. Problems with integrity of dataset – possibly caused by a post processing error though cause ultimately unknown.
Hrvoic and Pozza 2007	High resolution magnetic target survey	A ferrometallic object is detected by a magnetometer as it creates a magnetic field of its own that results in a local deviation from the earths magnetic field Magnetic anomalies represent the permanent magnetization of the object and the magnetization induced by the earths magnetic field A total field gradiometer : consists of two sensors mounted a set distance apart the difference in intensity is divided by the distance between the sensors giving a linear estimate

Reference	**Summary**	**Notes**
		of the gradient should not be affected by diurnal variations help to minimize geological background orientation of the axis between the sensors determines which individual component of the 3D gradient is measured (x, y or z) tend to enhance magnetic anomalies oriented in certain directions, which is undesirable in a small object survey result in data which are often harder to interpret. The analytical signal: is derived by measuring all three gradients (x,y & z) requires three sensors results in data which can be intuitively interpreted.
Reference	**Summary**	**Notes**
Kearney *et al* 2002	The principles and limitations of geophysical exploration methods An introduction to geophysical exploration – Blackwell Science	Page 3 - Magnetometer used to detect salt dome Page 155 - Most rock forming minerals are effectively non-magnetic. - Some rock types contain sufficient magnetic minerals to produce significant magnetic anomalies. Page 158 - 2 geochemical groups produce such minerals iron-titanium-oxygen (magnetite to ulvospinel) and iron-sulpher (Pyrrhotite). - The most commonmagnetic mineral is magnetite. Page 159 - Bar chart showing rock types and magnetic susceptibility. Page 162 - Early mag surveys (1900s) used magnetic variometers – essentially suspended bar magnets.

Reference	Summary	Notes
		- Fluxgate magnetometer developed and used in WWII. Page 163 - Proton Mag or nuclear procession total field accurate to +-0.1nT - Recently use of Overhauser effect makes this type more power efficient (25% of conventional type) and lower noise. Page 164 - Optically pumped or Alkali vapour sensitivity can be as high as +-0.01nT. - This precision not needed for total field measurements where background noise is of the order of 1nT. - Magnetic Gradiometers > any of the mag types can be paired to measure either vertical or horizontal mag field gradient. - **Mag gradients can also be measured by taking successive measurements with a single instrument at close vertical aor horizontal spacing.** - Gradiometers help resolve complex anomalies into their individual components. - They can determine location, shape and depth of the causative bodies. - Regional and temporal variations in the field are automatically removed. Page 165 - Diurnal variation correction - Take readings at fixed location throughout the survey (return to fixed location) - Can be inefficient in large survey area. - The base station should not be more than 100km from the survey area as diurnal variation is different in different locations. - Data collected in large high frequency variations (magnetic storm) should be discarded.
Li and Oldenburg 1998	Separating regional and residual data	Outlines four methods of removing regional and residual mag from data 1. Regional trend drawn manually 2. Regional trend estimated using least squares fitting of low order polynomial 3. Digital filter 4. Stripping Outlines and advocates stripping
Minerals Management	Archaeological damage by offshore	Pp 18 – 4.1: 'Today state-of-the-art magnetometers use cesium vapor or hydrogen ... for high

Reference	**Summary**	**Notes**
Service 2004	dredging. (Guidance doc.)	sensitivity and very low noise' Gradiometers provide amplified data about target bearing, size and orientation. Pp 39 – 7.2.3: Arnold (1980) and Bell & Nowak (1993) advocate the use of contour plots to interpret data. Pp 41 – 7.2.3: Bell & Nowak (1993) demonstrate that contour plotting data using run line spacing less than 20m affords better position extrapolation possibilities. Pp 43 – 7.2.3: Reliable analysis of data is dependant upon run line spacing. Pp 43 – 7.3: 30m run lines much the norm in USA. Florida recommends 30m inside the 100ft contour and 50m outside. North Coralina suggest 18m line spacing. Jacksonville district require 23m line spacing and two additional lines over each target identified. Pp 44 – 7.3: Institute for International Maritime Research has adopted 15m line spacing to identify 'early wrecks'.
Oxley and O'Regan (nd)	The marine archaeological resource	pp 20-21: 'Commercial survey data' of use in archaeological assessment only were survey equip. & methodology are suitable (ref. Draper-Ali 1996 and Marine Management Service 1994)
Oxford 2008	Guidelines for the renewable energy sector (Guidance doc.)	Nothing relevant
Pozza *et al* 2003	*Seaquest* marine gradiometer	
Sudhakar *et al* 2004	Werner deconvolution	
Tsivouraki *et al* 2003	Separating regional and residual data	
Van Den Bossche *et al* 2004	Maritime wreck survey	
Weiss *et al* 2007	Magnetic survey of shallow waters	Home made gradiometer using two optically pumped potassium mags attached to non-magnetic cat. Uses land based base station to subtract diurnal variation. Fig 5 shows corrected and uncorrected data for same targets
Wessex Archaeology 2003	Assessing, evaluating, mitigating and monitoring the archaeological effects of	Page 22

Reference	Summary	Notes
	marine aggregate dredging Guidance Note April 2003	- Magnetometer surveys are not used routinely in marine aggregate dredging surveys. - Trials have shown that mag survey may add to the results of bathy and SS survey. - Results can be interpreted archaeologically in conjuction with SS survey. - Line spacing for mag survey has to be <u>appreciably</u> closer than for SS if it is to be effective. Position Fixing - Positions to an accuracy of 1m or better horizontally and vertically. - Projection, co-ordinate system and vertical datum ... should be specified ... together with instrument layback.
Wessex Archaeology 2004	Guidance note on assessing, evaluating and recording wreck sites (Guidance doc.)	Pp 15 – 3.1.1: Position fixing of paramount importance in marine archaeological investigations. Pp 16 – 3.2.7: Possible error of greater than 100m between datums such as WGS84 AND OSGB36. Pp 16 – 3.2.10: WGS84 likely to be the definitive datum for the foreseeable future. Pp 16 – 3.3.1: Conventional GPS accurate from 4-20m Differential GPS accurate from 1-4m RTK centimetric accuracy but expensive. Pp 25 – 4.4.1: Mag functions by detecting variations in earths magnetic field generated by fe material on or under seabed. Pp 25 – 4.4.2: Mag theoretically able to detect non fe material such as fired clays etc. Pp 26 – 4.4.6: Principles of proton mag. Pp 26 – 4.4.7: Principles of caesium mag. Pp 26 – 4.4.9: Tow mag sufficiently behnd vessel to avoid detection of survey vessel. 'The magnetometer is typically towed near to the seabed along survey lines that are closely spaced'. Pp 26 - 4.4.10: Cubed relationship between signal strength and distance resulting in rapid diminishment of signal strength as distance increases. Pp 26 - 4.4.11: Line spacing of key importance Pp 27 – 4.4.12: Awareness of contaminated data (ie. passing vessels) important. Pp 27 – 4.4.13: data should be smoothed, corrected for layback and maintained as a xyz file. Pp 27 – 4.4.14: Various software options available for post-processing and interpretation.

Reference	Summary	Notes
		Pp 27 – 4.4.15: Use of Hall equation to estimate size of target. Pp 27 – 4.4.16: Amount of fe. material present in ports and harbours renders such areas hard to survey with mag Pp 28: 4.4.21/22: Mag of limited use for intra-site analysis/ investigation, particularly on iron wrecks. Pp 28 – 4.4.18: Awareness of diurnal variations pp 28 - 4.4.24: NS survey lines preferable were poss. As magnetic anomalies in British Isles will normally have a dipole field pattern oriented NS. Cross lines should be collected at 5 time typical line spacing. Pp 28 – 4.4.25: Caesium magnetometers or Overhauser proton precession magnetometers provide surficiently high quality data for archaeological use. pp 29 – 4.4.26: Interpreting site data as a contour plot impractical due to size of required dataset. Assessing individual 'lines' of data recommended. Pp 29 – 4.4.28: Gradiometers are not yet available in UK. When available will require new guidelines for use. Appendix X : Lists magnetic targets of less than 3nT total deflection.
Wessex Archaeology 2006a	Wrecks on the Seabed Round 2 Year 2 Geophysics Report (Guidance/Survey report)	2.4.1 - G-881 used on shallow sites, MM Explorer used on deeper wrecks. 2.4.2 - Depth Sensor on G-881 2.4.3 - MM Explorer towed 10m behind SS and assumed to be of the same altitude 2.4.4 - MagPick used to process and interpret data 2.4.5 - Mag amplitude graphs and surface plots used to id targets. 2.4.7 - Amplitude product of fe mass and distance to target Frequency indicative of distance to target. Surface plots used to refine position beyond that of closest approach. 3.1.1 - 2 x 2km search area, 25m line spacing. Each line surveyed twice – once with deep tow and once with shallow tow. 3.2.32 - Data selectively processed to replicate survey of 25/50/75/100 and 150m run line spacing.

Reference	Summary	Notes
		3.2.34 – Software limitations precluded three 'low frequency' anomalies from the dataset (?). 3.2.38 – Very interesting table of anomalies detected at different fish depth/line spacing (Table 17) 3.2.42 to 3.2.60 - elaborates on table 17 3.3.14 – Developed key descriptive terms for acoustic (ss) targets. Same needs doing for mag targets. 3.3.15 – Developed scale of arch. Potential of SS targets which they say should be informed by supporting mag data. 3.4.14 – Recommends running bidirectional run lines to help identify / correct layback busts 3.4.16 – Decrease in fish altitude of 10m resulted in 'considerably higher' no of detected anomalies. 3.4.17 – Hints that mag should be used in a supportive role alongside SS. 5.1.5 – Less than 10m difference in depth of fish between deep and shallow tow. 5.1.20 – Stresses the importance of human interpretation and the benefits of multiple analysts working to interpret the same dataset.
Wessex Archaeology 2006b	Salcombe Cannon Site, Devon Designated Site Assessment (Survey report)	5.2.1 – Geometrics G-881 used 70 lines at 10m spacing Data processed to remove regional and diurnal magnetic fields and exported as txt files Data gridded with field strength indicated by colour bands to id targets. 5.2.2 – 39 anomalies, only 2 believed to be of arch. Potential 6.4.9 – Anomalies with an amplitude of less than 5nT deemed unlikely to be of arch. significance General notes – No cross lines completed No mention of depth sensor/altimeter Water depth <25m Run lines oriented N-S No indication of fish depth/altitude No mention of layback / cable out

Reference	Summary	Notes
Wessex Archaeology 2007	Historic Environment Guidance for the Offshore Renewable Energy Sector	Summary: Use Caesium Gas or equivalent system capable of resolving anomalies of 5nT and above. 8.2.4 - Mag can help quantify amount of iron present - Can locate iron buried below seabed - Mag survey is unlikely to be conducted at line spacing sufficient to identify all anomalies in an area – so not appropriate for prospecting for wrecks – however useful when used in conjunction with side scan. 8.4.4 - As best practice archaeological survey should be incorporated with principal geophysical/geotechnical survey 8.4.5 - It may be helpful to have archaeological contractor onboard the survey vessel. 8.4.6 - Surveys should be carried out to a single co-ordinate system and datum preferably WGS84 UTM. 8.4.10 - Mag data should be made available as cleaned, de-spiked text (x,y,z) files for each line, including layback.
Wessex Archaeology 2008	Gull Rock Designated site report (Survey report)	3.2.1 – MM SeaSpy used @ 4Hz. Data recorded in Hypack. 3.2.2 – WGS 84 datum used. Positions fixed using a Trimble. UTM Zone 30 used. Layback apllied in post processing. 3.2.3 – Depth sensor used 3.2.4 – Unique file recorded for each run line 3.2.6 – Data exported from Hypack as txt file processed / interpreted in MagPick 3.2.7 – Layback, regional and diurnal variations processed in MagPick. Data gridded with field strength indicated by colour bands to id targets. 3.2.8 – Any anomalies with amplitude less than 5nT not recorded 4.2.1 – Survey area 500 x 300m. N-S run lines @ 10m spacing.

Reference	Summary	Notes
		4.2.3 – Layback 80 -200m Fish depth 5 – 18m (from 1/3 to ½ water depth. 4.2.6 – Area consisted of gravelly sand overlying igneous substrate. Geologies can be strongly magnetic in such areas and mask small anomalies. Data shows a series of dykes running across the dataset as broad monopoles.
Dix *et al* 2008	Marine Geophysical Instrumentation, acquisition, Processing and Interpretation.	Magnetometer section 4.4 4.4.1 Magnetic field intensity 24,000 nT at equator 66,000 nT at poles c. 50,000 around UK Magnetic field strength inversely proportional to the CUBE of the distance from the source. Recommends - Caesium vapour mag - Line spacing 30x30m (large area) - Line spacing 10x10m (Detailed) - Sampling interval > 1Hz - Fish Height < 6m - Speed 4 knots - Layback 2x vessel length - Positioning DPGS Proton Precession Sample rate 0.5 – 2 sec Sensitivity 0.2 – 1 nT Sensitive to heading errors – The total mag field over an object varies depending on towfish orientation. Overhauser

Reference	Summary	Notes
		An improved proton precession – better signal to noise Sample rate – 1 – 5 per sec Sensitivity – 0.015 nT/√Hz Accuracy – 0.1 – 0.2 nT Lower power consumption less heading errors Optically Pumped Even higher precision Sensitivity – 0.004 nT/√Hz Accuracy - <2nT Sample rate - <40 per sec Covers Diurnal variation – recommends using cross lines for correction 'at sea a land based station is not accurate enough' Gradiometers 4.4.3 Quotes Hall Equation 1 and 2 The smallest change in mag field that can be reliably detected is **5nT** Processing Heading correction, diurnal correction, Regional mag correction Presentation Line surveys, contour maps and isometric displays
		Final output an ASCII text file containing location, depth, adjusted magnetic value and (x,y,z) value