"Mircea cel Batran" Naval Academy Scientific Bulletin, Volume XVIII – 2015 – Issue 1
Published by "Mircea cel Batran" Naval Academy Press, Constanta, Romania // The journal is indexed in:
PROQUEST SciTech Journals, PROQUEST Engineering Journals, PROQUEST Illustrata: Technology, PROQUEST Technology Journals, PROQUEST Military Collection PROQUEST Advanced Technologies & Aerospace

ANALYSIS OFTHE TERRESTRIALMAGNETIC FIELDANOMALIESGENERATED BYUNDERWATEROBJECTS, USINGMAGNETOMETRY METHODS

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Abstract: *Study of the terrestrial magnetic field is a topical issue in the context of understanding and interpretation of anomalies generated by materials with ferromagnetic properties. Analysis of the earth's magnetic field changes, using magnetometry methods, allows detection on the surface, of these types of materials. This paper presents some elements of magnetic field theory and the way in which magnetometry data obtained in the Romanian seaside have been interpreted.*
Keywords: *magnetometry, total terrestrial magnetic field, magnetometer*

Introduction

The earth's natural magnetic field is responsible for inducing the magnetization in ferromagnetic objects. Although the highly nonlinear magnetohydrodynamics that takes place in the earth's core is not completely understood [1], the distribution of its main magnetic field over the world's oceans has been mapped [2], and is used in the prediction of a vessel's magnetic signature as a function of latitude, longitude, and heading.
According to these maps the values of earth'smagnetic totalfield for Romania seaside area range from 48,000 nT(2 Mai) and go up to 48.600- (Sulina -Musura Bay). The vertical component of the magnetic field has the largest share to total field and lies between 42.000nT and 43.000nT. To characterize the magnetic field direction we have the following components:

- **D** - declination - the angle between the geographic north and the projection of the terrestrial magnetic field vector (values between 0^0 and 360^0); On the Earth's surface it can be met areas of magnetic anomalies mentioned in maps for navigation as *abnormal magnetic variation*. In such areas magnetic declination value is different to that indicated in the map, because it contains magnetic minerals in the Earth's crust;
- **I -** inclination - the angle between the tangent to the earth's surface point and the direction terrestrial magnetic field vector (values between -90^0 and 90^0). In the Romanian seaside inclination value is about 45^0;
- magnetic equator - the line where the magnetic inclination value is zero (magnetic equator does not correspond to geographically);
- magnetic poles - the points where the magnetic inclination value is 90^0 -90^0 , respectively.

The module of terrestrial magnetic field density in Cartesian coordinates has the expression:

$$B = \sqrt{Bx^2 + By^2 + Bz^2} \quad (1)$$

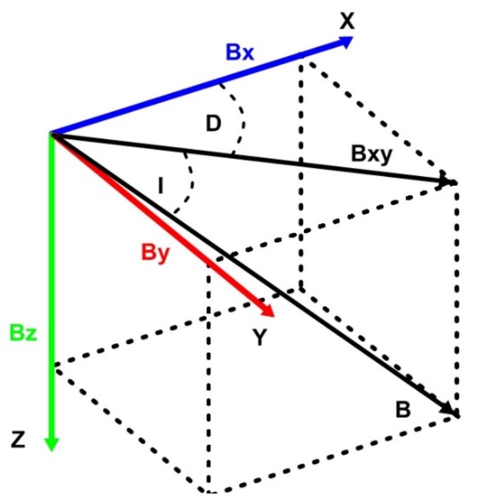

Figure 1. Terrestrial magnetic field components

Magnetic inclination $I = arctg\left(\frac{Bz}{\sqrt{Bx^2 + By^2}}\right)$ (2)

Magnetic declination: $D = arctg\left(\frac{By}{Bx}\right)$ (3)

Following some observations on the Earth's surface the terrestrial magnetic field is composed of three main distinct components:

- *Secular variations component*- variations in the main magnetic field that are presumably caused by fluid motion in the Earth's core (changes in the field that occur over years).;
- *Diurnal variations component* - These are variations in the magnetic field that occur over a day and are related to variations in the Earth's extemal magnetic field. This variation can be on the order of 20 to 40 nT per day and should be accounted for when conducting exploration magnetic surveys;
- *Magnetic storms component*- Occasionally, magnetic activity in the ionosphere will abrubtly increase. The magnetic field observed during such times is highly irregular and unpredictable, having amplitudes as large as 1000 nT. Exploration magnetic surveys should not be conducted during magnetic storms.

Induced magnetization and remanent magnetization. When a steel bar is placed in a uniform field not only is it magnetized as explained, but this magnetization also distorts the inducing field causing its flux lines to bend toward the steel. By convention, the magnetic field leaves the north pole of a magnet and enters its south pole. If the magnetized steel is moved across a sensor or if a sensor is moved past the steel, the anomalous field can be measured as a time-varying signal. This occurs whether the field is produced by an induced magnetization, permanent magnetization, or a combination of the two. [3].
The quantity characterizing the induced magnetization of the magnetic field is induced and is proportional to the energy and flux of the magnetic field generated by a constant referred to as magnetic susceptibility. Depending on the values susceptibility, magnetic materials can be classified as:

- Diamagnetic - is relatively low magnetic susceptibility with negative values;
- Paramagnetic - with relatively low magnetic susceptibility with positive values. Paramagnetism is associated with electron spin alignment direction in the presence of an external magnetic field and low temperatures can be observed in the material Curie temperature;
- Ferromagnetic - is a special case of paramagnetism when, the electron spin alignment on each field is parallel to the external magnetic field lines. For this type of material, depending on the orientation of electron spin we have the following classification:
    - Pure ferromagnetic - direction of domainsfor electron spins is parallel and in the same

direction with the external magnetic field lines (high positive magnetic susceptibility);

- Antiferromagnetic - for different magnetic domains have antiparallel orientation and the number of magnetic domains with antiparallel orientation is approximately equal (close to zero magnetic susceptibility);
- Ferrimagnetic - as the antiferromagnetic materials have different domains with antiparallel orientation but the number of each of the two directions is different. In this case, the orientation induced field is the same as the external magnetic field but with a much lower intensity than for the pure ferromagnetic materials.

The steel can be remnant magnetized (under the influence of terrestrial magnetic field due to the different routes traveled by ship). Unlike induced magnetization that disappears with the magnetic field who generated this induction, where remnant magnetization that remains after removal of the external magnetic field and is observed in materials with high magnetic susceptibility. This permanent magnetization can be represented in the same way as the magnetization induced by dipole type distribution. Dipole generated by induced magnetization has, as Earth's magnetic dipole, strength and direction.

For interpreting magnetometry data, the question is to estimate the distribution of magnetic dipole generated by a wreck and its influence on the terrestrial magnetic field (magnetic field anomaly).

Magnetometry measurements of terrestrial magnetic field. Magnetic anomalies.In general, using magnetometers it can be measured the total magnetic field intensity, but there are models that can measure magnetic field components in any direction. Ignoring the diurnal variations,we can say that the value of the measured total magnetic field at one point is the result of the mainly Earth's magnetic field component and the magnetic field induced in the rocks of the earth's crust or the ferromagnetic object. Change in the total magnetic field depending on elevation is less than 0,015 nT / m, so it can be neglected.

From the secular variation analysis of terrestrial magnetic field we can calculate the magnetic field for any point on the earth's surface, so it can be extracted from the data obtained from a survey, only anomaly field component.

In reality, for magnetometry data interpretation is very important to know the value of magnetic inclination for the area, to have a reference in determining the orientation of the bottom for an ferromagnetic object.

Data are usually obtained at a frequency of 2 Hz and are georeferenced by GPS. To do this, it requires knowledge of survey parameters such as[4]:

• ***Magnetometer towfish altitude*** (height above seabed). Most papersadvise that the towfish altitude must be determined by the minimum iron mass to be detected. The magnetometry data for this analysis were obtained for a 30 meters distance of the sensor to theshipwreck;

• ***Layback***. This parameter is required to calculate the magnetometer position because data is read from the magnetometer sensor.Dix et al (2008) state that the magnetometer layback should be equal to twice the survey vessel length. 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;

• ***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. Also,a particular importance for planning survey presents the orientationof these lines, NS magnetic direction or EW direction;

• ***Magnetometer type***. For our magnetometry survey was used Overhauser magnetometers type. This type is an improved proton precession magnetometer. A special liquid containing free, unpaired electrons is combined with the hydrogen liquid in the sensor cell. The sensor is irradiated with a radiofrequency magnetic field, causing these unbound electrons to transfer their energy to the hydrogen protons. The resultant precession signals have a higher signal-to-noise ratio than for a normal proton precession magnetometer. The Overhauser magnetometer sensitivity is 0.015nT/√Hz with an absolute accuracy of 0.1–0.2nT. Furthermore, the signals are non-decaying, which means that the polarization and signal measurement can occur simultaneously, leading to an increased sampling rate (between 1 and 5 readings per second).

• ***Position fixing*** was achieved by use of RTK GPS systems positioning with an error of less than one meter.It is preferred that georeferencing data obtained from other devices (multibeamechosounder, side scan sonar) to be made with GPS data from the same device, in this case all data will have a common time base.

• ***Tow speed and sample rate***. If we consider a magnetometer being towed behind a boat, the sensor will be moving forward and periodically (in accordance withsample rate)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 magnetometry data for this analysis were obtained at 3.5 knots speed of research vessel and magnetometer reading sample rate at 1Hz and 2Hz.

Magnetometry data acquisition was done by specialists of Maritime Hydrographic Directorate, using a system of total field magnetometry composed of two magnetometers, SeaSpy and Explorer. Acquisition and processing of georeferenced datamagnetometry was done with specialized software, such as: Sea Link, HYPACK, and Surfer 10 from Golden Software.

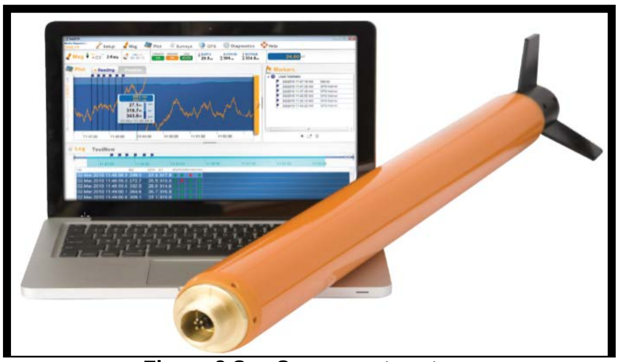

Figure 2. Sea Spy magnetometer (www.marinemagnetics.com/products/seaspy)

A. Interpretation of a magnetometry line depending of total magnetic field values. When a volcanic rock is cooled, its temperature falls below the *Curie temperature*. At the *Curie temperature*, the rock will present a induced magnetic field which will have the same orientation as that of the Earth's magnetic field. With the change in direction and intensity of Earth's magnetic field, induced field rock does not change and remains fixed in the direction of Earth's magnetic field at the time of cooling them. In general, the change in the magnetic susceptibility of rocks is conditioned by the presence of iron oxides constituents in the soil. Below, are some magnetic susceptibility values for different types of rocks (Table 1):

Table 1

Types of rocks	Susceptibility x 10^{-3} (SI)
Calcite	-0.001 - 0.01
Pyrite	0.05 - 5
Magnetite	1200 - 19,200
Sandstones	0 - 20

Schist	**0.3 - 3**
Gneiss	**0.1 - 25**
Granite	**0 - 50**

For the St. George - Sulina it can be seen a negative trend in the value of the magnetic field. This is in contradiction with the theoretical models for the terrestrial magnetic field and can be attributed to a large homogeneous geological structures (different magnetic susceptibility) [9].

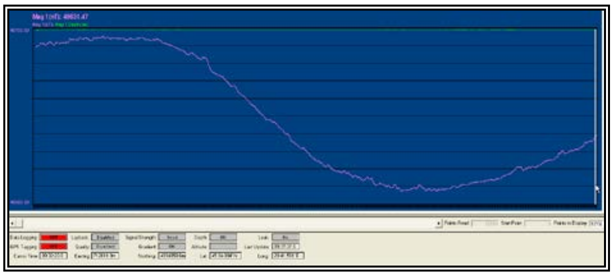

Figure3. Sf.Gheorghe-Sulina survey magnetometry line

For Mangalia - Tuzla can be notice a normal evolution of terrestrial magnetic field value. As characteristicit can be seena significant variations that occur in the upward trend of the magnetic field, variations attributable to the heterogeneous geological structures with different values of magnetic susceptibility (rocky bottom) [10].

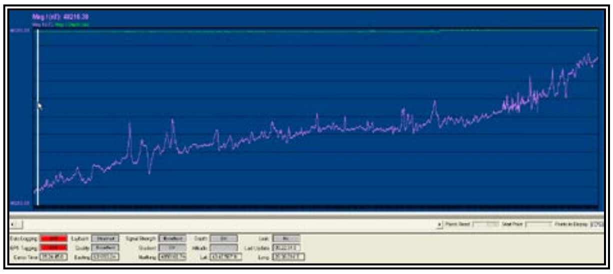

Figure 4. Mangalia - Tuzla survey magnetometry line

B. Data interpretation magnetometry for shipwrecks. One of the objectives of magnetometry survey,conducted by specialists of the MHD, was to identify and verify the position of a shipwreck at approx. 7Mn. travers fromCășla Vădanei in St. George - Sulinaarea. On this occasion, it was managed to determine the new position and classification of shipwreck.

The intensity of the magnetic field caused by ferrous objects depends on the size of the feature and more importantly, decreases with the cube of the distance to the object. To calculate the distance to a ferrous object it was use (Hall, 1966):

$$\Delta M = 10^4 \cdot \frac{A}{B} \cdot \frac{W}{D^3} \text{ [nT] (4)}$$

where ΔM is the change in field intensity (nT), $\frac{A}{B}$ is the length-to-width ratio of the object, W is the weight of the object in tons and D is the distance to the object (m). In practice, the smallest change in the magnetic field that can reliably be detected is 5nT. From this, the distance at which an object can be detected can be calculated:

$$D = \sqrt[3]{\frac{10^4 \cdot \frac{A}{B} \cdot W}{5}} \text{ [m] (5)}$$

For exemple:

- 400kg anchor (ratio ≈ 1) is detectable at 20m.
- 10 ton ship (ratio ≈ 5) is detectable at 46.5m.
- 100 ton ship (ratio ≈ 7) is detectable at 112m.
- 1,000 ton ship (ratio ≈ 10) is detectable at 271.5m.

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 $\chi = 633 \times 10^{-3}$ [m^3/kg].
Using omnidirectional dipole approximation as theoretical model [4], for a maximum level magnetic anomaly measured, to approx. 4500 nT at a depth of 30 m with 8 value of length-to-width ratio, it was estimate a shipwreck weight of approximately 1,700 tonnes (Fig 5).
It was noted that the first significant signal value was obtained at a distance of over 350 m from cross-checks, after which it switched to replanning survey lines on the area where the signal was obtained [9].

Figure 5 Chart with the magnetometry data acquired by Sealink software for a shipwreck located at 7Mn. travers of Cășla Vădaneiat 30 m depth

During the magnetometry survey it was acquired and multibeam bathymetry data. In the figure 6 are superimposed two georeferenced images - magnetometry and bathymetry. Magnetic anomaly measured at a towfish depth of 3m (30 m from the seabed) covers an ellipsoid area with semi-major axisof approx. 300 m, and small semi-axis of approx. 175m.From bathymetry dataresults ashipwreck length of approx. 70m and width of approx. 8m. Shipwreckorientation resulting from the two methods was identical - approx. 335^0.

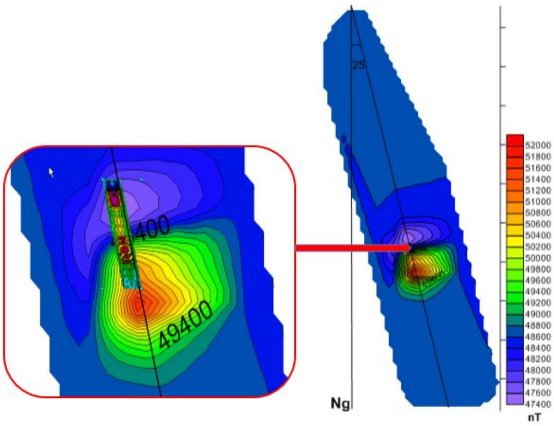

Figure 6. Magnetometry and bathymetrysuperimposed imagesof shipwreck

Methods for calculating the distribution of magnetic field strength, generated by a body of a certain shape, are complex. Theoretical models have been developed several types of elementary distribution forms such as sphere, cylinder and parallelepiped and a given body of a specific shape is composed of such elementary forms,for a good approximation.[6] The shape and distribution of the resulting magnetic field will be a combination of these patterns [5,7,8]. Such a procedure is quite complicated so, most times, for classifying the shape of a shipwrecks is taken into account only some general issues. For more details are used mutlibeam echosounders and side scan sonar surveysor this details can be obtain from in situ research,with divers.

In Figure 7 and Figure 8 it is shown, in 2D and 3D, distribution of a magnetic field anomaly specific to a ferromagnetic object located in the northern hemisphere, with orientation of remanent magnetization identical to orientation of terrestrial magnetic field.

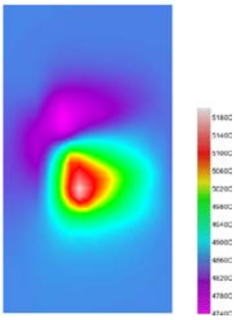

Figure 7. 2D image with magnetic field anomaly distribution

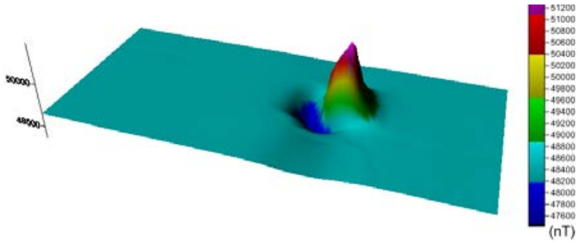

Figure 8. 3D image with magnetic field anomaly distribution

Conclusion

Using magnetometry system (SeaSpy and Explorer) can be drawn magnetic maps of an area and monitoring their changes in time, can be identified areas with magnetic anomalies also can be detected metallic submerged objects or covered with sediment at the sea bottom (including mine / unexploded ordnance).

The fact that, the detection of ferromagnetic submerged objects can be done at such a distance and variations of magnetic field in real time are marked on distance axis, recommends this method as superior to side scan sonar, singlebeam or multibeam methods.

Identification and classification of submerged ferromagnetic targets can be done fairly easily compared to other methods of investigation of the seabed (side scan sonar, singlebeam and multibeam).

Subsequent comparison of data magnetometry, with precise data obtained by other methods, for different types of targets can be a good base for future interpretation of detected targets.

Acknowledgements. Thanks to Hydrography and Oceanography Department staff of the Maritime Hydrographic Directorate for the data magnetometry provided to elaborate this work. In the future, collaborations in this field will be done through a better understanding of phenomena related to magnetic anomalies inducedin the earth's magnetic field by submerged objects.

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