6 Marine Magnetics

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6.1 Aim

The aim was to conduct a magnetic survey, using the *Explorer Magnetometer* towfish, in the surrounding area of the island Helgoland, located in the North Sea.

Using Multi Beam bathymetry, collected during the survey, the magnetic anomaly data was to be connected to seafloor geology (such as faults or ridges) or man-made objects (such as sunken ships or submarines).

6.2 Theory

Magnetic surveying is used to investigate subsurface geology by looking at anomalies in the Earth's magnetic field. Certain rock types in the subsurface have magnetic properties and can thereby cause small local distortions in the Earth's magnetic field. Furthermore, man-made ferrous objects, such as sunken ships or submarines can also generate sufficient anomalies, to be detected during a magnetic survey. [4]*(p.155)*

To investigate these magnetic anomalies, surveys can be carried out on land, at sea or in the air. Where land and seas surveys are more used in smaller local surveys with high resolution, airborne surveying is fast and can be used for larger areas. Magnetic surveying is also conducted from space using satellites to investigate the Earth's magnetic field in general or be used during space missions. [4]*(p.155)*

Instruments used during surveying are called magnetometers. *Fluxgate magnetometers* measure all three magnetic field components and are based on the nonlinear magnetization curve of magnetic materials. These kind of magnetometers are usually used in magnetospheric or interplanetary surveying. *Proton precession and Overhauser magnetometers* on the other hand only measure the scalar magnetic field magnitude. Their measurement is based on the principle of precession frequency of proton or electron spins under the influence of an external magnetic field. Further types include *Search coils* and *SQUID magnetometers*. [8]

At any given location the total magnetic field measured B_{total} can be expressed by:

$$B_{total} = B_{Earth} + B_{anomaly} \tag{6.1}$$

Therefore, using 6.1, the magnetic anomaly can be computed knowing the Earth's magnetic field at the designated surveying location.

6.2.1 The Earth's Magnetic Field

The Earth's time varying magnetic field is built up by a self-exiting dynamo process in the fluid outer core. Electrical currents flowing in the slowly moving molten iron outer core generate the Earth's magnetic field. The magnetic field observed on the Earth's surface has further sources in the crust, ionosphere and magnetosphere. [1]

The total geomagnetic field lies between values of $24,000nT - 66,000nT$ as can be seen in Fig. 6.1. [1]

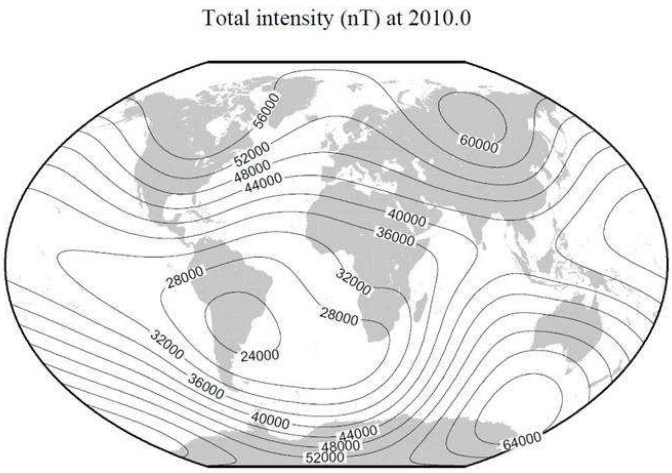

Figure 6.1: Contour map of total intensity (nT) at 2010.0

The geomagnetic field can be decomposed into a series of multipoles. The geomagnetic dipole is the dominant component. Where the geomagnetic dipole intersects with the Earth's surface lie the geomagnetic poles. The dipole axis is tilted at an angle of $\sim 11°$ to the Earth's rotational axis.

The geomagnetic field vector **B** at any point can be described by the following components. X (northward component/intensity), Y (southward component/intensity) and Z (downward component/intensity); declination (deviation from true geographic north) D; inclination I (the magnetic dip angle to the field vector; total intensity F (6.2) and horizontal intensity H (6.3). [8]

$$F = \sqrt{X^2 + Y^2 + Z^2} \tag{6.2}$$

$$H = \sqrt{X^2 + Y^2} \tag{6.3}$$

Earth's magnetic field is not constant but shows variation over time. This is mainly observed by geomagnetic observatories. Temporal variations are mostly caused by external sources on short time scales, but also by Earth's internal processes on very long time scales.

Magnetospheric and ionospheric current systems, which have influence on the Earth's magnetic field are susceptible on time scales of seconds up to decades. Events such as geomagentic pulsations and magnetic substorms can cause *diurnal variations*. Resulting changes to the measured geomagnetic field vary between $20 - 40nT$. *Magnetic storms* can cause variations of up to $1000nT$. Both diurnal and magnetic storm induced variations have to corrected for during magnetic surveying.[7]

Secular variations to the geomagnetic field can be caused by sunspot cycles lasting decades but also by changes in fluid motion in the Earth's outer core. [8]

Furthermore, the Earth's dipole can perform complete flips (*reversals*) in its dipole axis which usually take several millennia. Periods of one preferred orientation are irregular and can last between 100,000 of years up to several ten million years. These variations were established by analyzing directions and intensities of rock magnetisation from many sites around the world (such as ocean ridges). [1]

6.2.2 Magnetic Anomalies

Certain rock types contain enough magnetic properties to be superimposed on the local geomagnetic field and cause a magnetic anomaly. As the magnetic field varies in both amplitude and direction with location on the Earth, anomalies are asymmetric. Fig. 6.2 shows an example of a total magnetic field anomaly caused by an elongated body in the subsurface, approximated by a dipole. As can be seen, the total magnetic field anomaly is asymmetric around the location on the body. [4]*(p.170)*

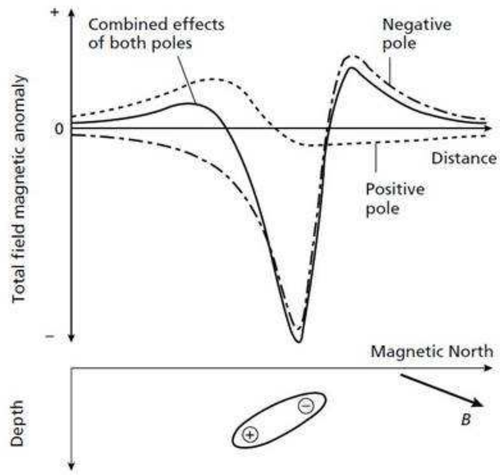

Figure 6.2: Total magnetic field anomaly of an elongated body

Different rock types show differences in magnetic susceptibilities, consequently having different influences on the local geomagnetic field. The induced intensity of magnetization is proportional to the susceptibility of the body [4]*(p.156-157)*. Equation 6.4 gives the total magnetic induction in a body B_i. k being the *magnetic susceptibility* of the material and H the magnetizing force.

$$B_i = (1 + k)\mu_0 H = \mu_0 \mu_R H \tag{6.4}$$

Interpreting geomagnetic anomaly data is highly ambiguous. For example the same magnetic variation can be caused by both rising metamorphosed sediments as well as detached oceanic crust. Using magnetic contour maps of the survey area can help to derive qualitative information and limit the ambiguity by controlling the possible nature and form of the causative body.[4](*p.167*)

6.3 Instruments: The Magnetometer

The instrument used in this magnetic survey is the *Explorer Magnetometer*, as seen in Fig. 6.3.

Figure 6.3: Explorer Magnetometer Towfish

Some specifications of the *Explorer Magnetometer* are given in Table 6.1. [6]

Length	86 cm
Weight (Air)	3.8 kg
Weight (Water)	1.2 kg
Absolute Accuracy	0.1nT
Resolution	0.001nT
Range	18,000nT to 120,000nT
Sampling Rate	4Hz - 0.1Hz

Table 6.1: Explorer Magnetometer Specifications

The *Explorer Magnetometer* is a *proton precession magnetometer* using the *Overhauser Effect* to measure the total magnetic flux at a given location and time.[5]

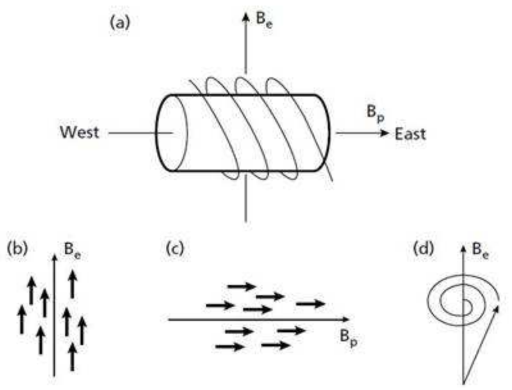

Figure 6.4: Proton Magnetometer principle

Fig.6.4(a) depicts the principle of a *proton precession magnetometer*. The device sensing and measuring the magnetic field flux is a liquid filled container, rich in hydrogen atoms (e.g. kerosene or water) surrounded by a coil. The protons (hydrogen nuclei),acting as small dipoles, align parallel to the ambient geomagnetic field B_e Fig.6.4(b). To measure the ambient geomagnetic field a current is passed through the coil inducing a magnetic field B_p about 50-100 times stronger than the ambient field. The hydrogen dipoles realign to B_p Fig.6.4(c). The polarizing field is switched of and the protons return to their original alignment with B_e by precessing around this direction with a certain frequency f Fig.6.4(d). Measuring f and using equation 6.5 then gives a very accurate measurement of the total geomagnetic field present. γ_p is the gyromagnetic ratio of the proton and known. [4](p.163)

$$f = \frac{\gamma_p B_e}{2\pi} \tag{6.5}$$

The *Explorer Magnetometer* uses the more advanced *Overhauser Effect* to acquire about an order of magnitude more precise measurements than the traditional *proton precession magnetometer*.

The *Overhauser Effect* is different in such a way that the liquid in the cylinder additionally contains unbound electrons. The *Overhauser Effect* makes it possible for nuclear populations to transfer their nuclear spin polarization to another population. In order to amplify the precession, the electrons additionally transfer their energies to the protons instead of simply emitting it. Thereby, the protons gain a higher polarization and precession. [2]

6.4 Data Collection

The magnetic field data was collected on five parallel north-south lines. The lines were chosen for a Multi Beam survey of an area north-west of Helgoland. Line spacing was 40 meters and each line had an average length of 3 nautical miles. The magnetometer was used during the Multi Beam survey. Table 6.2 shows the specifics for the different lines. Lines 1,3 and 5 were northward, 2 and 4 southward. The data was collected on the $15^{th} of April 2013$.

Line	Time(UTC)	Longitude	Latitude	Length [m]
1	12:35-12:48	424451.1-424483.1	6006585.3-6008652.6	2067
2	12:51-13:19	424394.7-424629.1	6008663.2-6004253.3	4410
3	13:20-13:41	424660.5-424642.8	6004355.3-6008089.4	3734
4	13:48-14:06	424714.7-424691.7	6008421.2-6005125.4	3296
5	14:13-14:30	424727.1-424741.8	6004545.7-6008078.0	3524

Table 6.2: Data collection Lines - 15.04.2013

The magnetometer towfish is towed behind the research vessel. A $65m$ tow cable is used for this survey (the $250m$ cable was defect). The large tow length is necessary to prevent magnetic field distortions by the huge metallic vessel. Figure 6.5 shows a sketch of the survey set-up. (The size of the magnetometer relative to the vessel is highly exaggerated.)

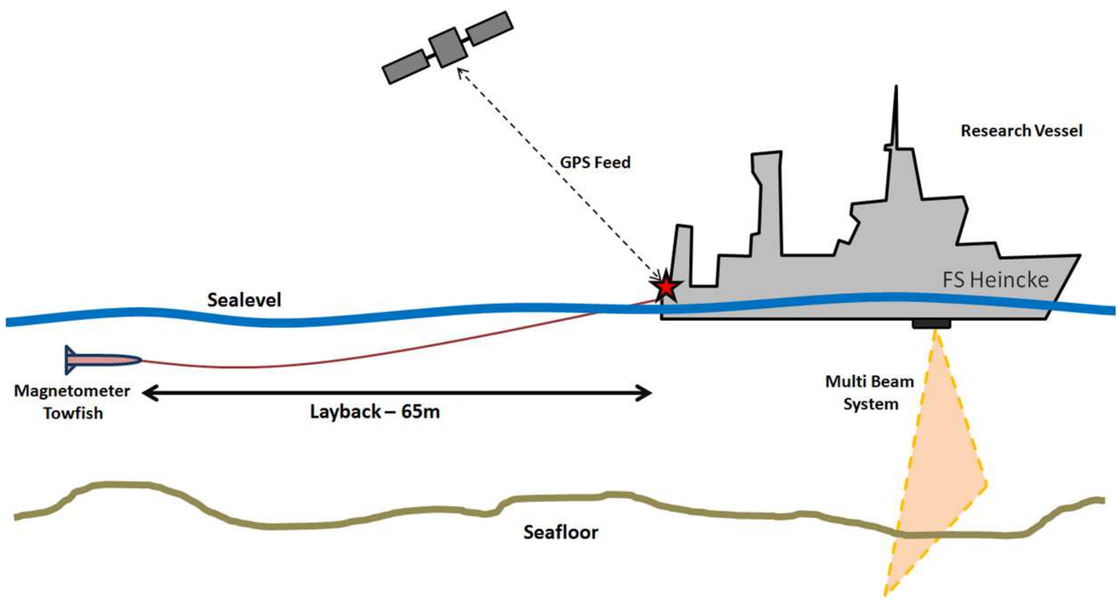

Figure 6.5: Data collection Set-Up

The red star in Fig. 6.5 represents the station set-up. From here the towfish is passed into the sea and the data is recorded on a "Toughbook" laptop. To connect the laptop (via RS-232) to the magnetometer and necessary power supply (AC power) a cable splice point is used. (Fig. 6.6) Additionally, a hand-held GPS is connected to the laptop to GPS-tag the towfish location during the survey. [5]

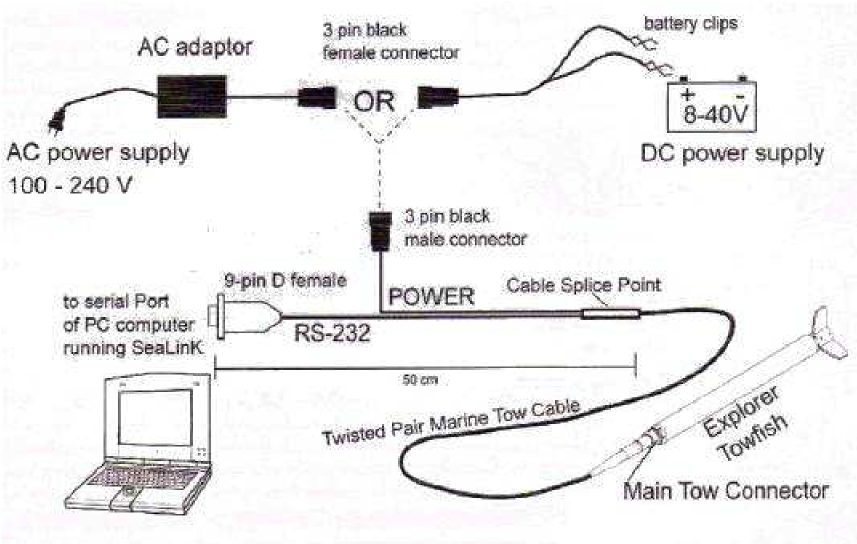

Figure 6.6: Data collection Set-Up

The program *Sealink* is used for data collection. The following procedure is used to collect the survey data for one line. [5]

- Before lowering the towfish into the water the pressure sensor is set to *zero pressure* in *Sealink*. Now the atmospheric pressure above water is used as the reference value for 0 depth. (This did not work properly during this survey.)
- The towfish is synced to the GPS by pressing the *GPS synch* button in *Sealink*. The program is now synced to the GPS position and time of the hand held GPS device.
- Now the towfish can be lowered into the water slowly.
- In *Sealink* the *Layback* is set to 65 meters. As the GPS is on the boat additional 65 meters have to be added or subtracted from the GPS data.
- *Sealink* is used to tag the GPS to the towfish
- Sampling rate set to $1Hz$
- Data collection is started by pressing *Log Data* in *Sealink*.

As the ship turned after each line the magnetometer had to be pulled in several meters to prevent damaging the device due to reduced ship speed and the towing length. After the turn was completed the towfish was let out further again. This explains why the line length in Table 6.2 shows line lengths shorter than the designated $3nm$ $(5556m)$.

Fig. 6.7 shows a Time Series plot of the collected total magnetic field data.

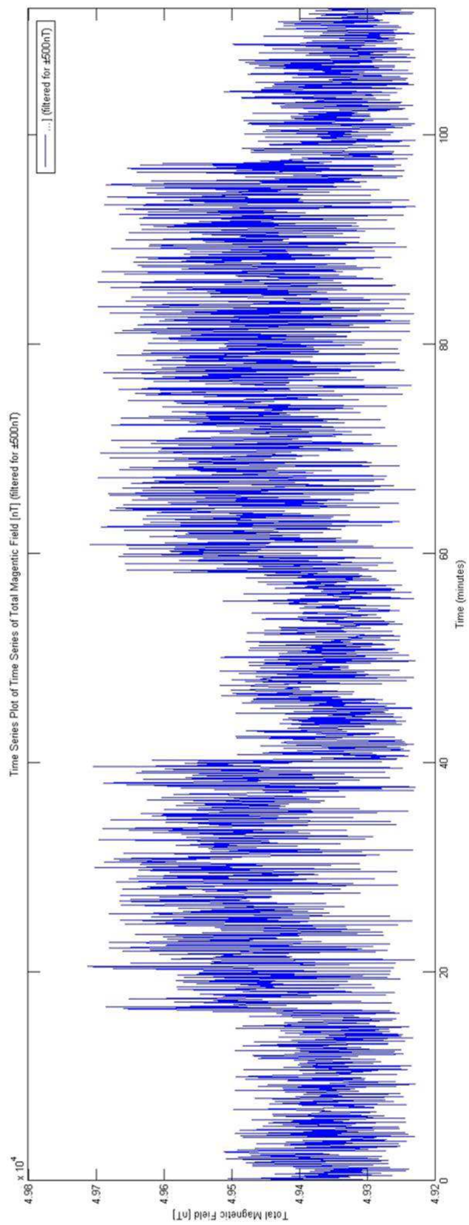

Figure 6.7: Total Magnetic Field recorded by the Magnetometer

6.5 Data Processing

To process the collected data the designated data files were opened in *Excel.* All irrelevant and unnecessary data columns were deleted. Left for processing were the Time, in UTC, the total measured magnetic field value *[nT]*, and the GPS coordinates, UTM 32N.

As explained in 6.2 the measured total magnetic field values are composed out of the Earths magnetic field IGRF and the local magnetic anomalies. To calculate these local anomalies the IGRF has to be subtracted from the collected data. (See 6.1)

To do this the correct IGRF value for the total magnetic field at the survey location has to be determined. Furthermore, if any variations in the Earth's magnetic field were present during the survey time, these have to be accounted for.

The International Real-time Magnetic Observatory Network (short INTERMAGNET)is a world-wide network of geomagnetic observatories monitoring the Earth's magnetic field 24/7. [3]. From here the daily variations in the Earth's magnetic field can be checked at different locations. The closest one to the survey area is Wingst, Lower-Saxony. When looking at the recorded data from Wingst (one reading every minute), one can see that the diurnal variation during the survey time (12:35-14:30 UTC) is $\Delta B_{diurnal} < 5nT$ and can therefore be neglected.

The IGRF correction value for the area around Helgoland is $49628.2nT$. Observing at the Multi Beam data collected at the survey area shows that no big metallic objects (such as sunken ships or submarines) were present to cause large anomalies in the magnetic field. Therefore, the range of plausible anomalies was $\pm 400nT$ to the expected magnetic field values. All values $(49228.2 < B_{total} < 50028.2)nT$ were filtered out, leaving plausible values to further work with.

An example of the collected data and calculated anomaly can be seen in Table 6.3.

Time(UTC)	eastings	northings	total Mag. Field [nT]	Anomaly [nT]
13:08:02.0	424532	6005857.8	49619.035	-9.165

Table 6.3: Example collected Data

The plotted anomaly data then looks similar to Fig. 6.7 with strongly varying data values between north and southward headed lines. One possible reason for these measurement errors is a so called *heading error* caused by the research vessel.

To correct for this measurement error the following steps are carried out in *Microsoft Excel*:

- The median of all recorded and filtered anomaly values of one line is computed.
- The computed median of all northward heading lines and southward heading lines are compared. If they are about the same a heading error is present.
- The difference between the average northward and southward median is calculated.
- The newly computed value is used to correct the the higher median values (either all north- or southward lines). In this case all northward lines were corrected.

In addition to the anomaly correction, the UTM northings have to be slightly adjusted. Since the Multi Beam System is located in the front third of the ship, the Multi Beam bathymetry data is GEO-tagged at that position on the ship. But as the data was collected and GEO-tagged at the aft of the vessel the additional layback to the Multi Beam system has to be taken into account to correctly correlate the anomaly to the seafloor structure. Therefore, $25m$ are added to all northward $Y(northing)$ coordinates and subtracted from all southward $Y(northing)$.

All corrected anomaly values and their respective UTM coordinates are saved in form of a *.csv* file.

GMT is used to create a median grid with a $20m$ radius to better display the data.

ArcCatalog is used to create a respective feature class out of the measured anomaly values. The z-values are given by the anomaly. The used coordinate system is UTM 32N.

The same procedure is used to create a bathymetry feature class from the Multi Beam data.

Both feature class shape files are opened in ArcGIS. The bathymetry map is interpolated to create a profile of the seafloor. This profile is overlain by the measures total magnetic anomalies to create an anomaly map. (Fig. 6.8)

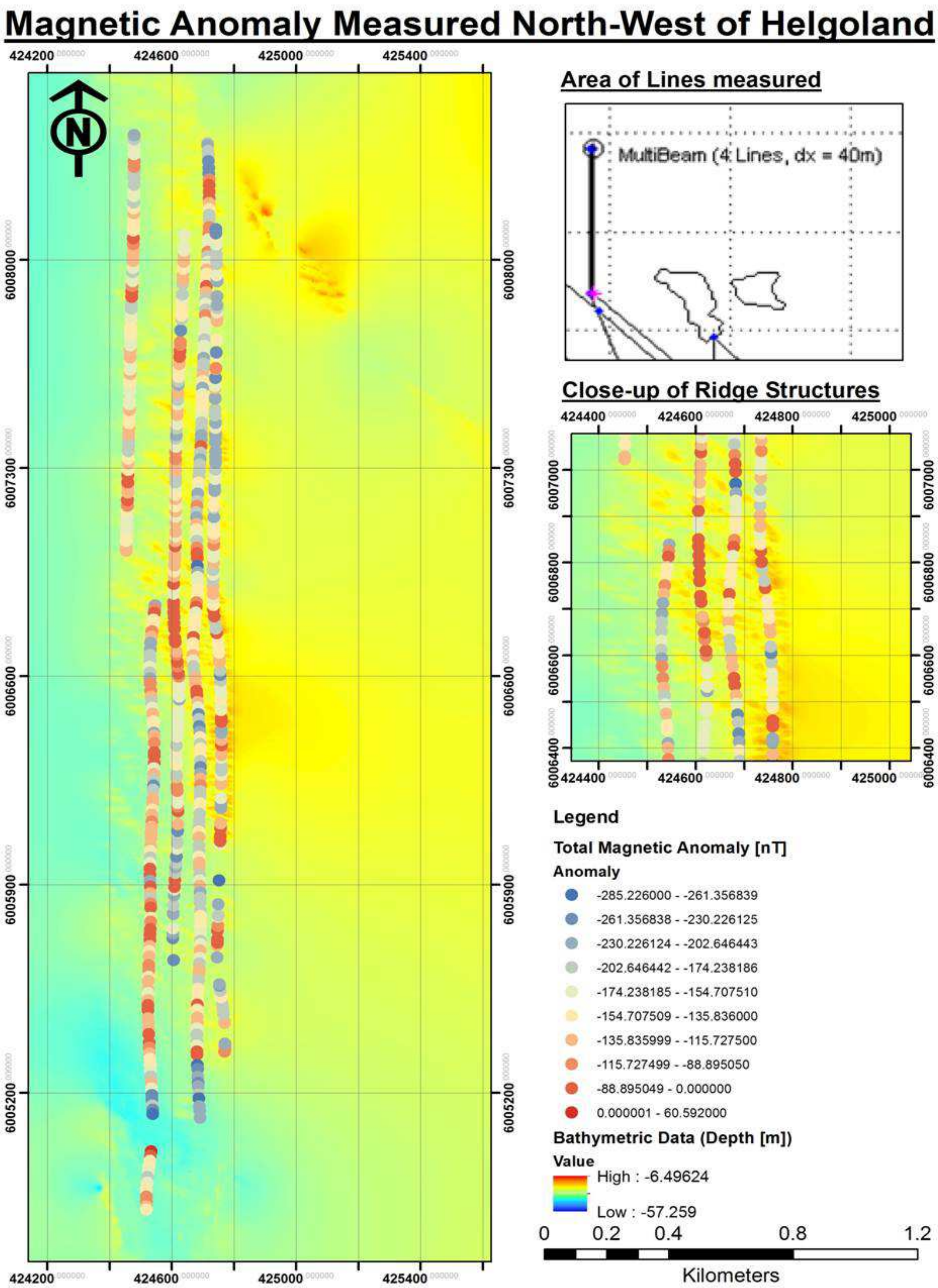

Figure 6.8: Magnetic Anomaly Map plotted over Bathymetric data measured North-West of Helgoland

6.6 Results and Analysis

The results of this geomagnetic survey are represented by the anomaly map seen in Figure 6.8.

In the upper right-hand corner the *Area of Lines measured* shows the picked survey plan. One extra line was taken.

The big anomaly map shows the collected and filtered anomaly data plotted over the Multibeam bathymetry data. The total magnetic anomalies vary from $-285nT$ to $+60nT$ and are plotted in ten classified intervals. Most of the anomalies are negative. Lines 1 and 2 are both intensively filtered and only half way through the line the data values become reasonable. Lines 3-5 all seem to be in a reasonable range for almost the entire line. The whole survey area shows prominent ridge structures running from the south-east to the north-west. This can be deducted from the bathymetry data. Most of the survey area has a depth of about 25 meters but the seafloor rises to about a depth of 10-15 meters at the ridges.

A *Close-up of Ridge Structures* depicts a magnified view of very prominent ridge structures and the overlying magnetic anomaly values. Line 3 seems to have very dense positive or only slightly negative anomaly variations directly above the ridges.

In general, certain south-east to north-west trends in the anomaly data can be seen. Not all, but some of the measured values seem to align over the ridge structures going in the same south-east to north-west direction. This would imply that the changes in seafloor structure can be detected by changes in magnetic properties seen in the anomaly data.

6.7 Discussion and Conclusions

As described in the *Data Processing* section 6.5, the collected geomagnetic data had to be intensively filtered, corrected for heading error and gridded as median values.

The high variability in the collected data and heading error were most likely caused by the to short tow cable. As the rule of thumb is to tow a magnetometer at a distance of 2-3 times the ship length, the 70 meter cable used was too short. The *FS Heincke* has a length of 55 meters and would therefore require a tow length of ideally ~ 170 meters. Unfortunately the 250 meter tow cable was defect and the 70 meter cable had to be used. Consequently, the measured total magnetic field intensity was most probably influenced by the huge metallic body of the ship.

Nevertheless, the few trends in the anomalies over the ridge structures indicate that a magnetic survey over this area could produce good data if carried out using the proper tow length.

The magnetometer also seemed to need a certain amount of time to ”warm-up”, as both the first halves of lines 1 and 2 did not record any reasonable data. Also the magnetic readings after turning of the ship to start a new line, seem to be off at the beginning.

To increase the quality of a prospective survey the following adjustments should be made:

- Use a tow cable of 2-3 times the ships length. When on the *FS Heincke* using a 250 meter cable would be optimal.
- Give the magnetometer one line to ”warm-up” where no readings are necessary.
- Designate the survey lines ins such a way that ”bad data after turning” is accounted for.
- Connect the Laptop (or other recording device) to the same GPS-system the *Multibeam* and possible *Parametric Echosounder* use. This will ease possible correlations of magnetic data to seafloor structure and subsurface geology.

From the survey area the close-up seen in Fig. 6.8, with the most prominent ridge structures, would be the most promising sub-area to re-survey and further investigate. A grid of 6 north-south lines (1.5 km long between 6005900 and 6007400 north) and 5 east-west cross lines (0.5 km length between 424300 and 4245800 east) with line spacing of 100 meters between lines and 250 meters between cross lines would be a possible set-up.

Bibliography

[1] BGS. The earth's magnetic field: An overview, 2013.

[2] GEMSytsems. Overhauser magnetometer, May 2007.

[3] INTERMAGNET. Intermagnet, September 2010. Wingst Observatory.

[4] Hill Kearey, Brooks. *An Introduction to Geophysical Exploration.* Blackwell Science, 2002.

[5] Marine Magnetics. *Explorer - Operation Manual.* Marine Magnetics Corp, revision 1.21 edition.

[6] Marine Magnetics. Explorer - mini marine magnetometer, 2012.

[7] Unnithan. Lectures 14-15-16: Magnetics, April 2013.

[8] Joachim Vogt. Magnetisim of planet earth. pdf, 2013.