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# Marine Vector Magnetometer on RRS Discovery

Seismology and Geomagnetism

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# Marine Vector Magnetometer on RRS Discovery

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# Foreword

This report describes the instrument calibrations and data processing made to test the BGS technique for measuring the strength and direction the geomagnetic field at sea. The data were acquired from the RRS Discovery during a survey campaign in the North Atlantic.

# Acknowledgements

We would like to thanks all the BGS staff that have contributed to this project and the crew of the RRS Discovery. Special acknowledgement is due to Collin Brett who was responsible for the survey campaign and Michael Wilson who looked after the equipment on board the RRS discovery.

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# Summary

The report describes the work undertaken as part of a feasibility study in using an established technique for estimating the absolute strength and direction of the geomagnetic field at sea. Measurements were made on board the RRS Discovery during a survey campaign in the North Atlantic during August 2003. The problem differs from previous marine vector magnetometer tests in that the RRS Discovery is a large steel vessel with a very large associated magnetic signal and, due to cost limitations, the Attitude and Heading Reference System (AHRS) was of lower accuracy than previously used. In a similar procedure to previous surveys, the measuring equipment was calibrated on land prior to being taken to sea. Whilst at sea, the magnetic field of the vessel was estimated by swinging the vessel through 360° before and after the survey. Our main goal was first to check that the magnetometer gave an accurate reading despite the very strong gradient of the vessel's magnetic field, second to estimate if the AHRS was sufficiently accurate and then to check that our processing technique was valid for data acquired on this type of vessel. After data processing it becomes clear that the magnetometer responds correctly to the variation of the magnetic field onboard the vessel but the AHRS is not accurate enough to adequately determine the magnetometer orientation in normal surveying mode. However, the data are accurate enough to estimate, with reasonable accuracy, the direction of the field at the swing site. The same results holds for our processing technique: it failed for data acquired in normal surveying mode due to anisotropic susceptibility of the vessel, but give results accurate enough at the swing site. Future modification of our acquisition system should include temperature control and an AHRS capable of better representing the magnetometer orientation.

# 1 Introduction

In August 2003 the NERC vessel RRS Discovery was chartered by BGS to sail a series of seismic survey lines in the North Atlantic. We took the opportunity to test, on this large steel vessel, our equipment for measuring the absolute value of the geomagnetic field vector at sea. The technique was previously developed for use onboard the TSMY Adventurer (Lesur et al. 2004), a light 35 m long fibreglass vessel designed for a round world record attempt for a motor vessel, and therefore generating a relatively small magnetic field (of the order of 150 nT) on deck. In this situation, we have been able to successfully estimate and correct for the vessel magnetic deviation field. In undertaking trial of the equipment on the Discovery, we had the three following objectives:

- Check that the vector magnetometer we used is reliable in an environment with very strong magnetic field gradients.
- Check that the Attitude and Heading Reference System (AHRS) in place on the vessel is accurate enough for our needs.
- Check that our processing technique holds for a large steel vessel.

None of these points can be tested outside of real survey conditions. On the RRS Discovery, there are numerous possible sources of magnetic noise and her mass of steel is so large that it is impossible to foresee how the vector magnetometer will react. During the original surveys using the TSMY Adventurer, we had use of a very accurate, but expensive, POS/MV Model 320 AHRS. The AHRS in place on the RRS Discovery has a lower accuracy, but the vessel's behaviour at sea is likely to be much slower and smoother than the TSMY Adventurer. And finally, the success of our processing technique relies on the assumption that the bulk susceptibility of the vessel is isotropic. It is not known if such an approximation holds for the RRS Discovery. Ideally we would be able to successfully correct for the full vessel deviation magnetic field and our technique would be made available for academic application. In the worst scenario we would have collected some useful information on the general behaviour of a large vessel at sea, further understood the reliability of our magnetometer and have obtained an estimate of the amplitude of the magnetic signal of a large steel vessel.

This report is organised as follows: in the next section we present the concept of our measurement, calibration system and instrumentation; Sections 3, 4, 5 and 6 describe the calibrations of the magnetometer, of the frame & magnetometer pair, of the vessel & frame pair and of the vessel alone respectively; and we list our conclusions in Section 7.

# 2 Concept and instrumentation

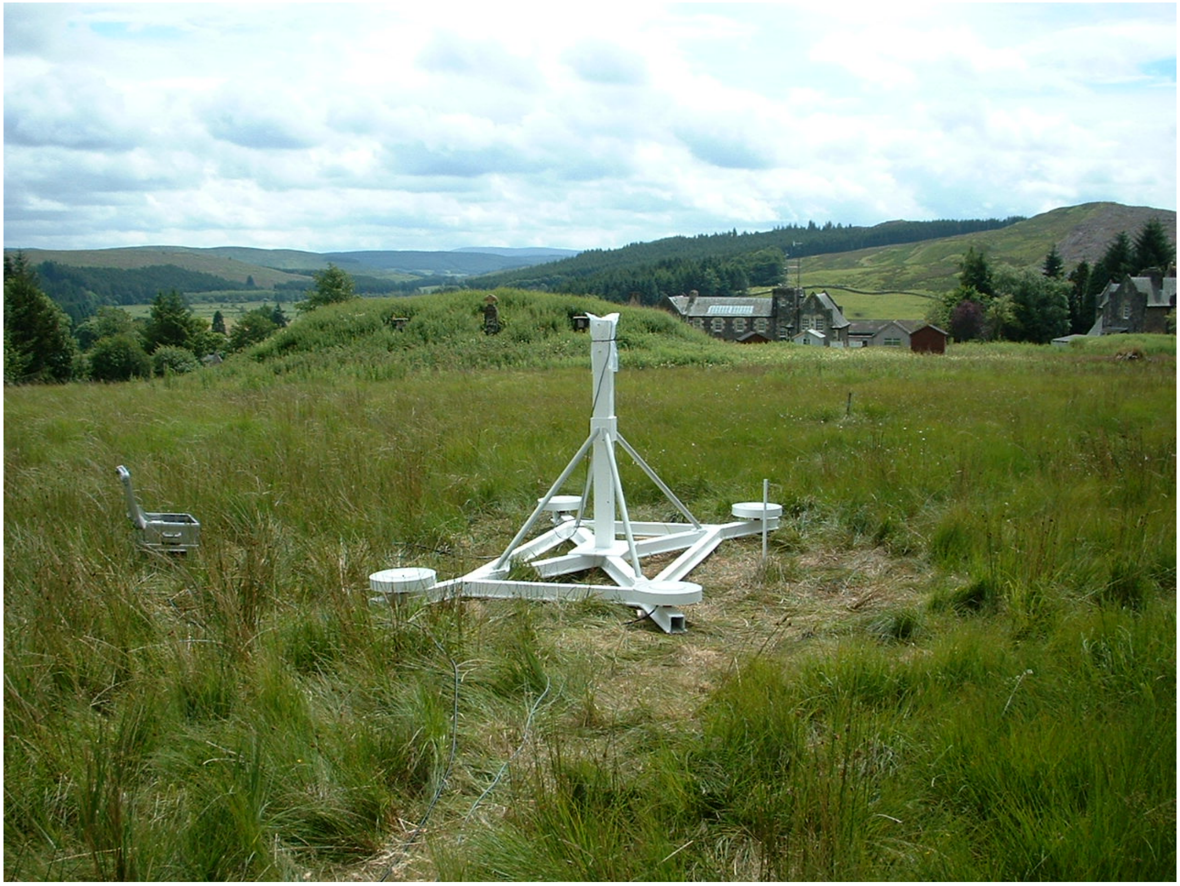
The concept of the system is quite straightforward: the tri-axial magnetometer is mounted on a rigid fibreglass frame together with the Attitude and Heading Reference System (AHRS). When set on the vessel, the system outputs three orthogonal vector components of the magnetic field as well as the heading, pitch and roll of the vessel. The magnetic and attitude data are then used to estimate the vector magnetic field in a geographic reference frame. The difficulty comes from the need to accurately align the magnetometer and attitude sensor, and more especially to remove the vessel's magnetic field from the measurements. These unknowns are determined during the calibration process, and the accuracy of the final magnetic data will be strongly dependent on the success of this process.

The instrumentation we used during the August 2003 campaign is similar to the system outlined in Lesur et al (2004) and is not fully described here. The instrumentation differs only in the AHRS system and the shape of the fibreglass frame. On the RRS Discovery is permanently mounted a navigation system that includes a differential GPS and an Ashtech ADU2 receiver. The Ashtech ADU2 system attitude specifications are 0.2° root mean square (rms) dynamic heading and 0.4° rms dynamic pitch and roll accuracy for a GPS receiver array of 1 m square. On the vessel we expect to exceed these accuracies. This AHRS system is capable of delivering 1 Hz data and was taken as our primary system. Since the ADU2 is mounted on the vessel but part of the calibration must be completed away from the vessel's magnetic field, a secondary, less accurate, AHRS, was mounted directly on the frame with the magnetometer.

Figure 1 shows the fibreglass frame fitted with the four GPS antennas of the secondary Ashtech 3DF AHRS. A Bartington Instrument MAG-03MCL70 tri-axial fluxgate magnetometer is fixed inside the top of the vertical section. This vertical section is 1.5 m high and the base is a 2.5 m by 2 m rectangle. A Guralp DM24 digitiser (in the aluminium box) is used to sample the three components of the magnetometer at a rate of 100 Hz. The data from the primary and secondary AHRS systems are time stamped using the GPS receivers, as are the data from the digitiser, allowing data between systems to either be directly compared, or compared through interpolation.

The first step of the calibration process estimates the scaling factors and offsets of the system composed of the magnetometer and digitiser, as well as the angles between the magnetometer sensors. The second stage of the calibration requires that the magnetometer be mounted on the rigid frame such that the orientation of its sensors may be estimated relative to a coordinate system defined by the secondary AHRS. This orientation is defined as three rotation angles. Once these orientations are established, the frame is mounted on the vessel and both primary and secondary AHRS are run simultaneously in order to determine three other rotation angles that define the transformation from the coordinate system of the primary AHRS to that of the secondary AHRS. At this point we are able to transform the vector magnetic field measured by the magnetometer to a geographic reference frame. The last step of the calibration, completed with the frame mounted on the vessel, estimates the magnetic field of the vessel.

**Figure 1 Fibreglass frame at the calibration site in Eskdalemuir. The four GPS antennae can be seen on the frame. The magnetometer is at the top of the vertical section, inside.**



# 3 Magnetometer calibration

The offsets and scaling factors of the magnetometer-digitiser pair were measured before and after the Discovery survey campaign by rotating the magnetometer in a place where the magnetic field strength and direction are known. Details on vector magnetometer calibration can be found in Turbitt & Clark 1997. The results of these two first calibrations made inside the West Hut at Eskdalemuir Observatory are given in Table 1. The “on site” values are measured at the frame & magnetometer calibration site (Fig. 1) but scaling values are not available because the total intensity magnetic field value is not accurately known and therefore is solved for during the calibration process. The “on site” values cannot be directly compared with the other values due to the temperature differences between the calibration sites. For the calibration in the absolute hut, it can be seen that the scaling factors are stable in time with less than 0.06% variations but there are discontinuities in the magnetometer-digitiser offsets which we think are introduced when the instruments are switched off/on. These discontinuities are harmless since they will be mapped in the vessel remanent magnetic field. The variations of the collimation angle are less than 0.06°.

**Table 1 Magnetometer-digitiser calibration results at Eskdalemuir (magnetometer: MAG-03MCL70 1202; Digitiser: D0754)**

| | | 01/07/2003 | 28/11/2003 | |
|---|---|---|---|---|
| | | (in abs. hut) | (in abs. hut) | (on site) |
| Offsets (counts) | X | -4431.50 | -4388.74 | -4330.140 |
| | Y | -2663.50 | -1769.08 | -1840.57 |
| | Z | -315.50 | -343.13 | -352.11 |
| Scaling (counts/nT) | X | 40.7731 | 40.7828 | - |
| | Y | 40.6196 | 40.6437 | - |
| | Z | 40.7576 | 40.7519 | - |
| Angles (degrees) | YZ | 89.9106 | 89.8806 | 89.8673 |
| | XZ | 90.0089 | 89.9817 | 89.9827 |
| | XY | 89.7796 | 89.7287 | 89.7316 |

# 4 AHRS-Magnetometer calibration

Once the AHRS and magnetometer were mounted on the frame, two calibrations were performed; before the measurement campaign during July 2003 and then after the measurement campaign during September, October and November 2003. The first calibration was affected by a power failure, which potentially changed the offsets of the magnetometer-digitiser pair. We used only the data from the second calibration period.

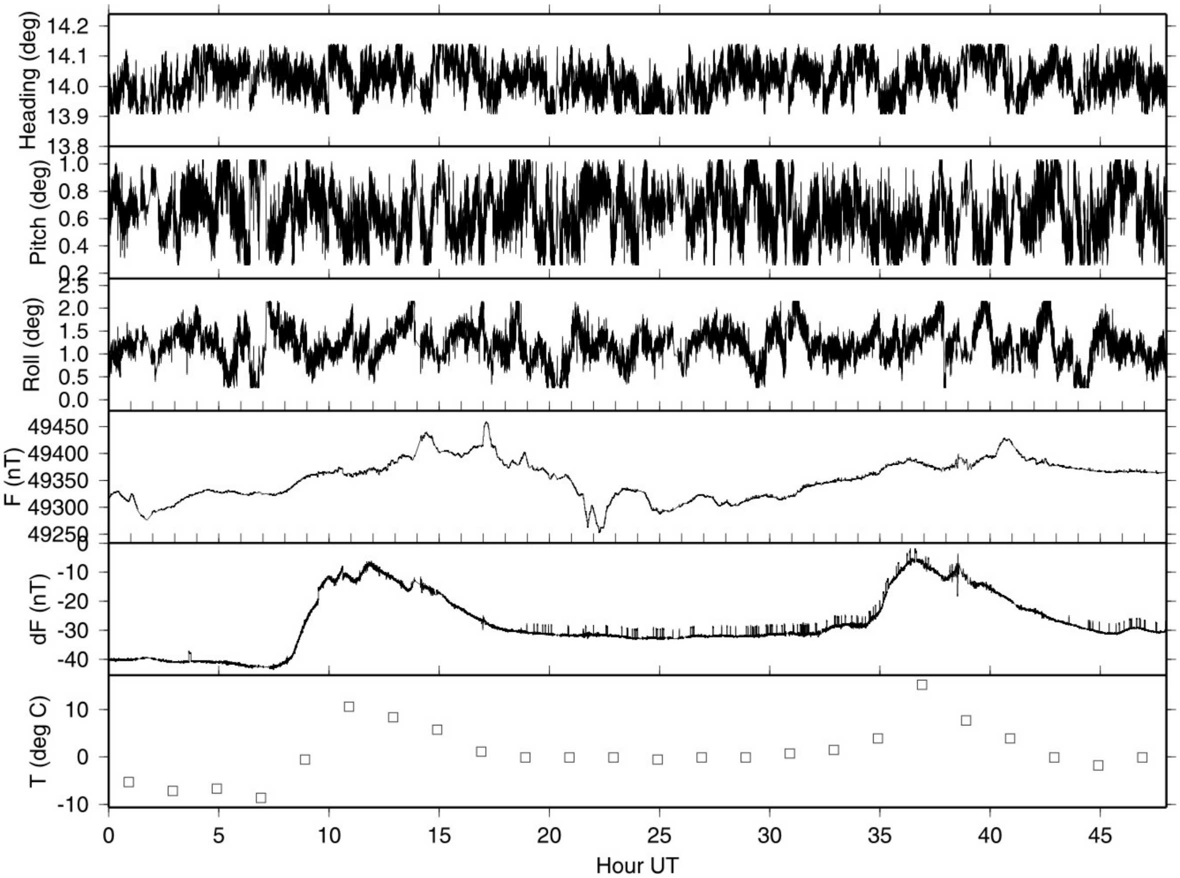
The outputs of this calibration are three rotation angles $\omega_i \; i = 1,2,3$ that describe the transformation between the magnetometer and the AHRS reference frame i.e. the magnetic vector in the AHRS reference frame $\boldsymbol{b}_{AHRS}$ is calculated from its value in the magnetometer reference frame $\boldsymbol{b}_{MAG}$ by:

$$\boldsymbol{b}_{AHRS} = \boldsymbol{\Omega}_3 \; \boldsymbol{\Omega}_2 \; \boldsymbol{\Omega}_1 \; \boldsymbol{b}_{MAG} \qquad (1)$$

where $\boldsymbol{\Omega}_i \; i = 1,2,3$ are three orthogonal rotation matrices associated with the three angles $\omega_i \; i = 1,2,3$. Since the AHRS data give a transformation from the geographic reference frame to the AHRS frame, a manual absolute measurement of the strength and direction of the field vector can be transformed to the AHRS frame, giving $\boldsymbol{b}_{AHRS}$. The three rotation angles can then be determined from equation (1) using measures of $\boldsymbol{b}_{MAG}$ for a number of different frame orientations.

For this calibration, the frame was site outside the West Hut at Eskdalemuir Observatory, where the magnetic gradients are low and where magnetic field strength and direction were known. James Carrigan measured the magnetic field strength and direction on 26/06/2003, and calculated an average offset of 0.142° in declination, -0.126° in inclination and 13.97 nT in total intensity relative to the Eskdalemuir Observatory data. Figure 2 shows 48 hours of data acquired on 21/10/2003 and 22/10/2003, where the flagged and inaccurate AHRS data have been rejected. Also shown are the total intensity data (F) as measured by the magnetometer on the frame, the difference between F and the total intensity estimated from the observatory data (dF) and the temperature (T) measured over the same period every two hours. Although the frame attitude was fixed during this period, the measured heading, pitch and roll (H, P and R respectively) are all very noisy, but the accumulation of data over several days allows a robust estimation of average values. Over the two days in Figure 2, the averages in H, P and R are 14.02°, 0.64° and 1.22° respectively.

**Figure 2 AHRS outputs the 21/10/2003 and 22/10/2003 for a static position at Eskdalemuir. Shown as well are the measured total intensity values, their differences with the estimated total intensity values and the temperature.**




During this calibration the differences in total intensity (dF) should be zero, however, the fluxgate magnetometer offsets and scales have a temperature dependence and there is a very good correlation between dF and T. Furthermore, the magnetometer is not exactly at the site where absolute data were measured and the observatory baseline varies with time introducing a further discrepancy (~3.2 nT). However, for the calibration we can choose data values for which dF is in the interval [-5 nT : 5 nT], thus limiting the errors due to temperature dependence. The three rotation angles ($\omega_i \ i = 1,2,3$) were derived from a data set of three frame orientations, each orientation comprising a series of magnetic data values. Table 2 gives the frame directions as heading, pitch and roll values, their standard deviations (SDs) and the number of magnetic vector data associated with these directions.

The obtained three angles were:

$\omega_1 = 93.339 \text{ deg}$

$\omega_2 = 1.232 \text{ deg}$

$\omega_3 = 180.865 \text{ deg}$

These rotations affect only the direction of the vector not its amplitude. In Figure 3 and 4 are shown the declination and inclination of the magnetic field estimated from observatory data together with the declination and inclination estimated from our system. The rms differences between the two are 0.048° in declination and 0.055° in inclination. For clarity the data are shown as a continuous line but they were acquired on different dates. For declination and inclination, the largest differences are for record numbers from 125000 to 150000, corresponding to the position 1 data set. The discrepancies between estimated and observed declination and inclination are due to an imperfect magnetometer calibration for the temperature range in Eskdalemuir in autumn. In particular the Z scaling factor is probably slightly underestimated.

**Table 2 Heading, pitch and roll of the three data sets used to determine the magnetometer orientation in the secondary AHRS reference frame**

| | | Angles (deg) | SDs (deg) | Number of vector magnetic data |
|---|---|---|---|---|
| Position 1 | H | 14.021 | 0.0059 | 27 567 |
| | P | 0.639 | 0.1930 | |
| | R | 1.217 | 0.3672 | |
| Position 2 | H | 281.328 | 0.0061 | 104 585 |
| | P | 0.711 | 0.1420 | |
| | R | -0.373 | 0.2579 | |
| Position 3 | H | 100.672 | 0.0077 | 124 330 |
| | P | -0.125 | 0.1727 | |
| | R | -0.602 | 0.3581 | |

**Figure 3 Estimated and measured declination at Eskdalemuir for the magnetometer & frame calibration pair**

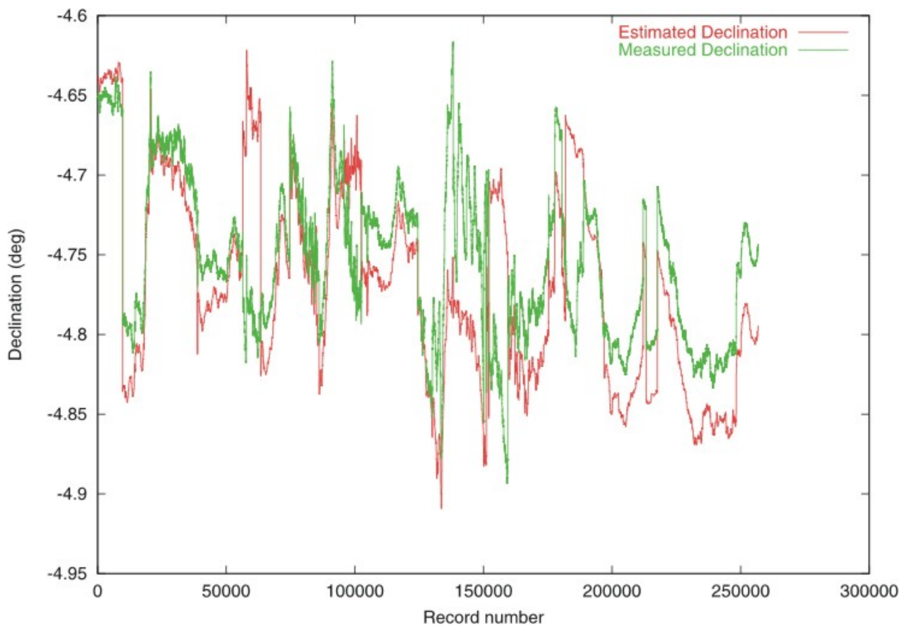
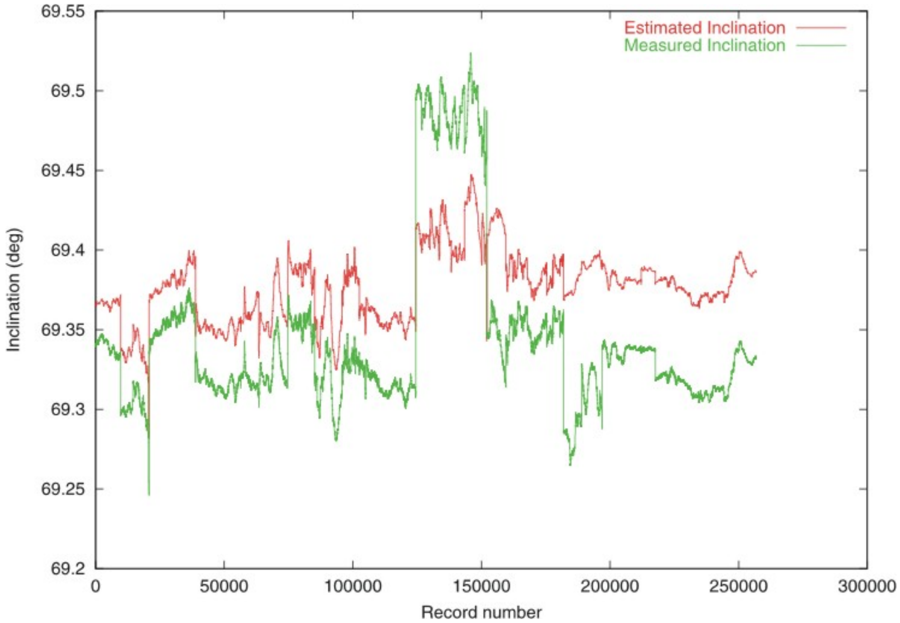


**Figure 4 Estimated and measured inclination at Eskdalemuir for the magnetometer & frame calibration pair**



# 5 Vessel-Frame calibration

During the vessel-frame calibration we try to estimate the three rotation angles $\sigma_i \; i = 1,2,3$ associated with three orthogonal rotation matrices $\boldsymbol{\Sigma}_i \; i = 1,2,3$, which give the expression of the magnetic vector in the secondary AHRS reference frame $\boldsymbol{b}_2$ relative to its expression in the primary reference frame $\boldsymbol{b}_1$. This transformation is written:

$$\boldsymbol{b}_2 = \boldsymbol{\Sigma}_3 \; \boldsymbol{\Sigma}_2 \; \boldsymbol{\Sigma}_1 \; \boldsymbol{b}_1 \tag{2}$$

If we call $\boldsymbol{H}_i, \boldsymbol{P}_i, \boldsymbol{R}_i \; i = 1,2$ the three rotation matrices associated with the heading, pitch and roll in the primary or secondary AHRS reference frame, then the expression $\boldsymbol{b}_1$ and $\boldsymbol{b}_2$ as function of the magnetic vector $\boldsymbol{b}_{geo}$ in the geographic reference frame is:

$$\begin{aligned} \boldsymbol{b}_1 &= \boldsymbol{R}_1 \; \boldsymbol{P}_1 \; \boldsymbol{H}_1 \; \boldsymbol{b}_{geo} \\ \boldsymbol{b}_2 &= \boldsymbol{R}_2 \; \boldsymbol{P}_2 \; \boldsymbol{H}_2 \; \boldsymbol{b}_{geo} \end{aligned} \tag{3a \& 3b}$$

Therefore the angles $\sigma_i \; i = 1,2,3$ can be computed from the relation:

$$\boldsymbol{\Sigma}_3 \boldsymbol{\Sigma}_2 \boldsymbol{\Sigma}_1 = \boldsymbol{R}_2 \; \boldsymbol{P}_2 \; \boldsymbol{H}_2 \; \boldsymbol{H}_1^{-1} \; \boldsymbol{P}_1^{-1} \; \boldsymbol{R}_1^{-1} \tag{4}$$

For one heading and attitude of the vessel, the relation 4 is a system of three unknowns (the $\sigma_i \; i = 1,2,3$) and nine equations. With the vessel moving, the matrices $\boldsymbol{H}_i, \boldsymbol{P}_i, \boldsymbol{R}_i \; i = 1,2$ are time dependent but the angles $\sigma_i \; i = 1,2,3$ and their associated orthogonal rotation matrices $\boldsymbol{\Sigma}_i \; i = 1,2,3$, do not depend on time. By solving the equations 4 for several vessel headings and attitudes, the angles $\sigma_i \; i = 1,2,3$ are very robustly estimated.

The frame with the GPS antennas and magnetometer was mounted on the top of a fibreglass container on board of the RRS Discovery on 12 August 2003 (Figure 5). We used the fibreglass container as a support to keep the magnetometer away from the steel mass of the vessel and other containers. The vessel left Govan (Scotland, UK) at 7:05 GMT on 13 August 2003 and the AHRS data for a full day (the 14th) was used to estimate the angles $\sigma_i \; i = 1,2,3$. During that day, 62618 AHRS data (i.e. 72.5% of the 1 second data) were measured simultaneously by both the primary and secondary systems with the required accuracy leading to the three angles:

$$\sigma_1 = -151.4609^\circ$$

$$\sigma_2 = 0.0498^\circ$$

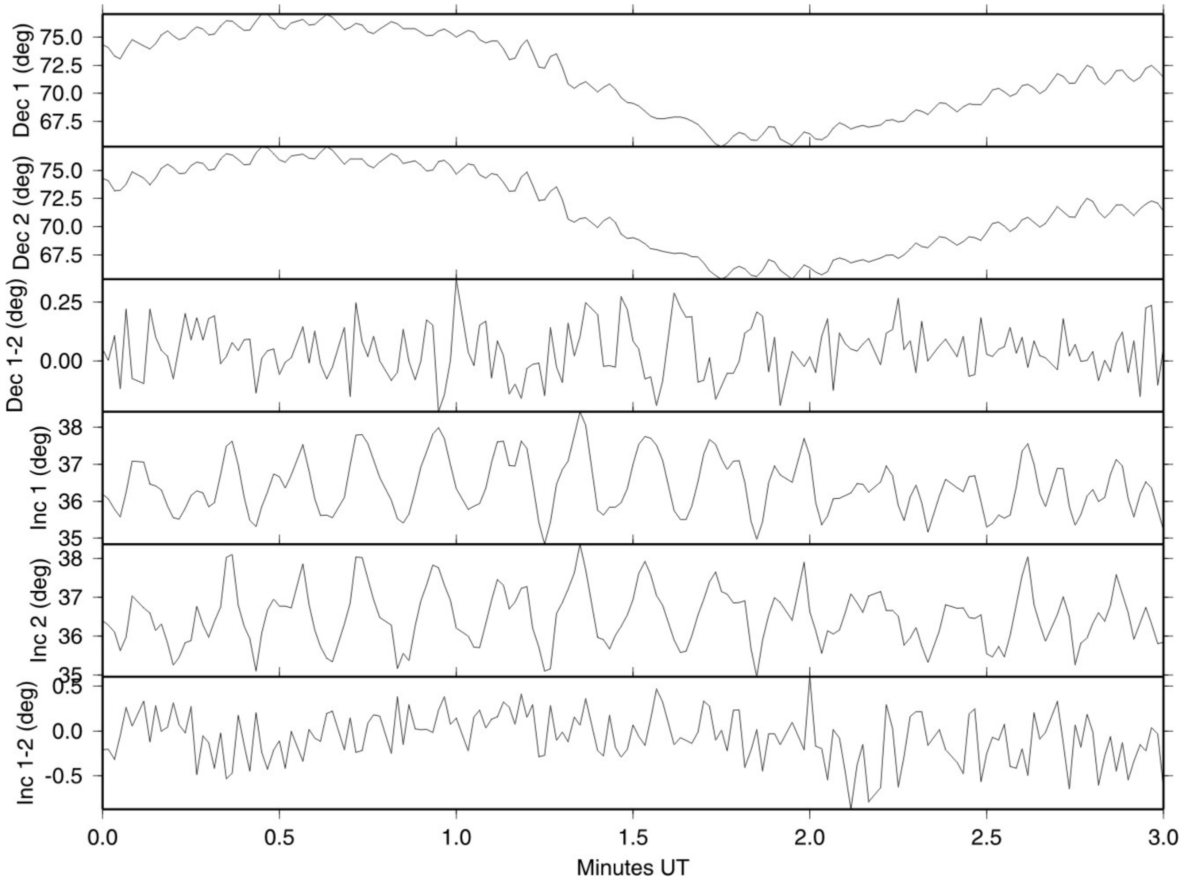
$$\sigma_3 = 0.6144^\circ$$

To estimate how accurate the AHRS data are, an arbitrary vector direction fixed in the geographic reference frame was chosen ($\boldsymbol{b}_{geo} = (1,1,1)^t$). Then, the coordinates of this vector in the primary AHRS reference frame were calculated either directly from equation 3a, or from the secondary AHRS using equations 3b and 2. Figure 6 presents these coordinates (in terms of declination and inclination) and their differences for three minutes at 00:00UT on the 14/08/2003. Over the 62618 values acquired that day, the standard deviations of their differences (including periods where the vessel swung by 360°) are 0.21° in declination and 0.43° in inclination. By comparison with the data gathered at Eskdalemuir Observatory, the secondary

AHRS system appears less noisy when subject to the motion of the vessel, and, as at Eskdalemuir, the heading is more accurate than the pitch and roll. The two systems may show correlated errors due to a poor distribution of GPS satellites, and these errors cannot be estimated here. It is not absolutely obvious from these data, but we will see later, that the primary AHRS is the more accurate of the two.

**Figure 5 Frame with antennae and magnetometer mounted on the top of the white fibreglass container reinforced with red steel bars, on the stern deck of the RRS Discovery.**

**Figure 6 Comparison between the primary and secondary AHRS. The declination and inclination of an arbitrary vector is computed directly (Dec 1, Inc 1) or via the AHRS 2 reference frame (Dec 2, Inc 2). Also plotted are the differences.**



# 6 Estimating the vessel signal

In this last calibration step the magnetic field generated by the vessel is estimated. The vessel's field $\boldsymbol{b}_1^v$ in the primary AHRS coordinates system, can be calculated using a matrix $\mathbf{A}_1$ and a vector $\boldsymbol{r}_1$ by:

$$\boldsymbol{b}_1 = \boldsymbol{b}_1^i + \boldsymbol{b}_1^v = (\boldsymbol{I} + \boldsymbol{A}_1)\boldsymbol{b}_1^i + \boldsymbol{r}_1 \tag{5}$$

where $\boldsymbol{b}_1$ and $\boldsymbol{b}_1^i$ are the measured and inducing magnetic field (i.e. the ambient field) in the primary AHRS coordinates system respectively. The vector $\boldsymbol{r}_1$ represents the remanent part of the vessel field whereas the product $\boldsymbol{A}_1\boldsymbol{b}_1^i$ is its induced part. In the following we will assume that the equations are written in the primary AHRS coordinate system and drop the subscript 1. To fully estimate the vessel field for a given attitude, the matrix $\boldsymbol{A}$ and the vector $\boldsymbol{r}$ have to be estimated. This is done by a 360° turn of the vessel at a site where the inducing magnetic field $\boldsymbol{b}^i$ is known. Unlike previous surveys, it was not possible to directly measure the total intensity at the swing site, away from the effect of the vessel, so the intensity has had to be estimated. Other authors have used a magnetic field model to approximate $\boldsymbol{b}^i$. Here we will use a geomagnetic field model to estimate its strength and otherwise follow the methodology, in particular to deduce the inclination and declination of $\boldsymbol{b}^i$, as described in Lesur et al. 2004. The inducing magnetic field is estimated in the AHRS coordinate system using either:

$$\boldsymbol{b}^i = \boldsymbol{R_1}\ \boldsymbol{P_1}\ \boldsymbol{H_1}\ \boldsymbol{b}^i_{geo} \tag{6}$$

or

$$\boldsymbol{b}^i = \boldsymbol{\Sigma}_1^{-1}\ \boldsymbol{\Sigma}_2^{-1}\ \boldsymbol{\Sigma}_3^{-1}\ \boldsymbol{R_2}\ \boldsymbol{P_2}\ \boldsymbol{H_2}\ \boldsymbol{b}^i_{geo} \tag{7}$$

All these matrices being orthonormal, relations 6 and 7 have no effect on the strength of the field. The measured magnetic field $\boldsymbol{b}$ is estimated from its value in the magnetometer reference frame $\boldsymbol{b}_{MAG}$ by:

$$\boldsymbol{b} = \boldsymbol{\Sigma}_1^{-1}\ \boldsymbol{\Sigma}_2^{-1}\ \boldsymbol{\Sigma}_3^{-1}\ \boldsymbol{\Omega_3}\ \boldsymbol{\Omega_2}\ \boldsymbol{\Omega_1}\ \boldsymbol{b_{MAG}} \tag{8}$$

The set of measurements used to estimate the vessel signal were acquired at 07:26 GMT, 14 August 2003 at 57.268° latitude North, -8.0511° longitude East, to the West of the Hebrides Isles i.e. 195.741 km E, 6358.790 km N in UTM zone 30. Figure 7 shows the total intensity anomaly field over the area and the expected anomaly at the swing site is around –70 nT ± 100 nT encompassing all levelling errors. This day was magnetically quiet and the estimated total intensity of the external field varied between 0 nT and 15 nT during that morning. The total intensity output of the current British Global Geomagnetic Model (BGGM2003) at the swing location for that date is 49997 nT. Our best estimate of the inducing field strength at the swing site is therefore 49942 nT and we will assume that the associated error is ± 100 nT.

**Figure 7 Aeromagnetic total intensity anomaly data (in nT) around the vessel swing site**

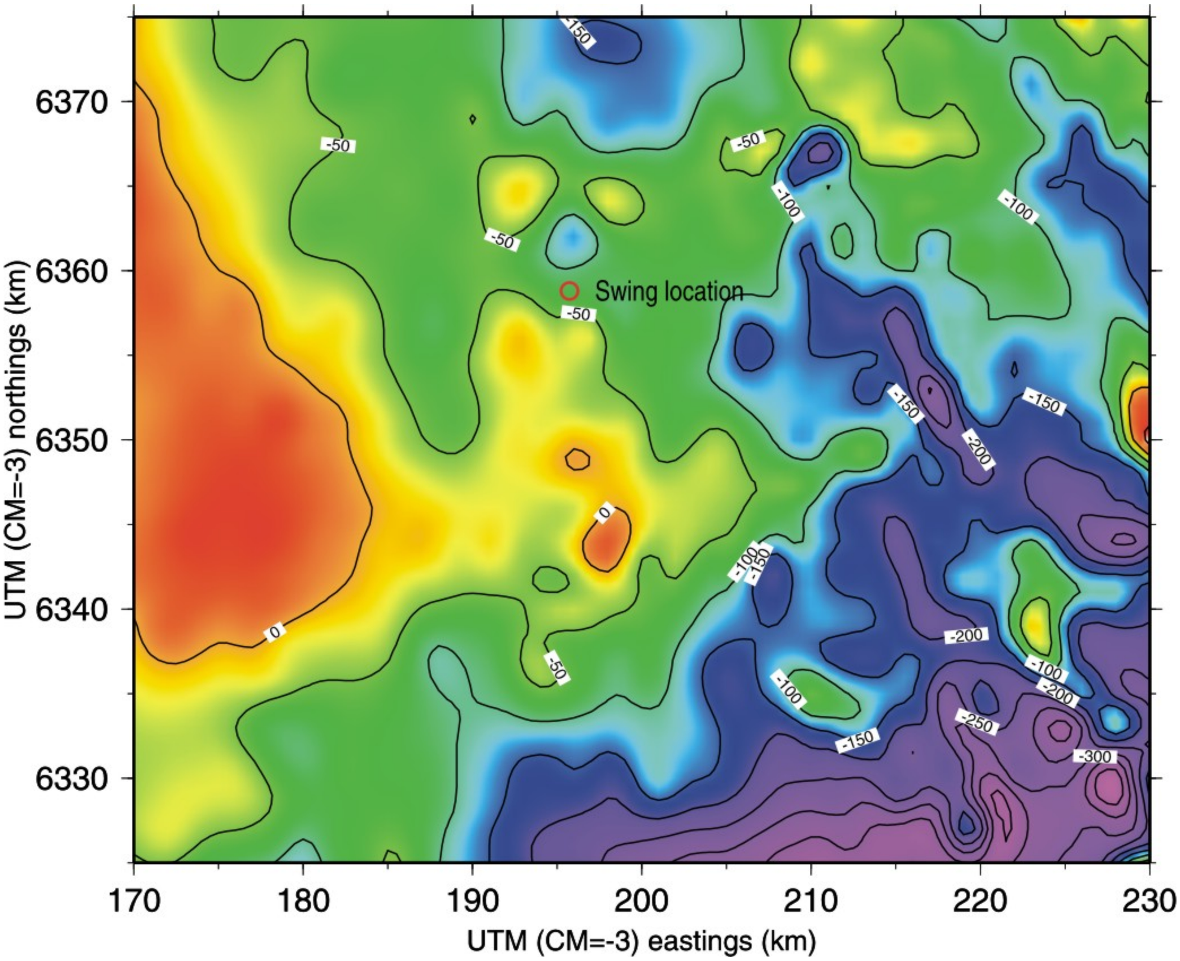



Figure 8 shows the raw measured total intensity and the total intensity corrected for the vessel signal. The raw total intensity shows a heading dependent signal of 4623 nT amplitude superimposed on an average signal of 46013 nT. The coherency of the signal shows that the magnetometer outputs are valid despite the severe gradients of the magnetic field on the vessel. The corrected values average around the imposed value of 49942 nT without clear heading dependency.

**Figure 8 Measured raw total intensity values and values corrected for the vessel signal at the swing site. The average 49942 nT total intensity is imposed.**

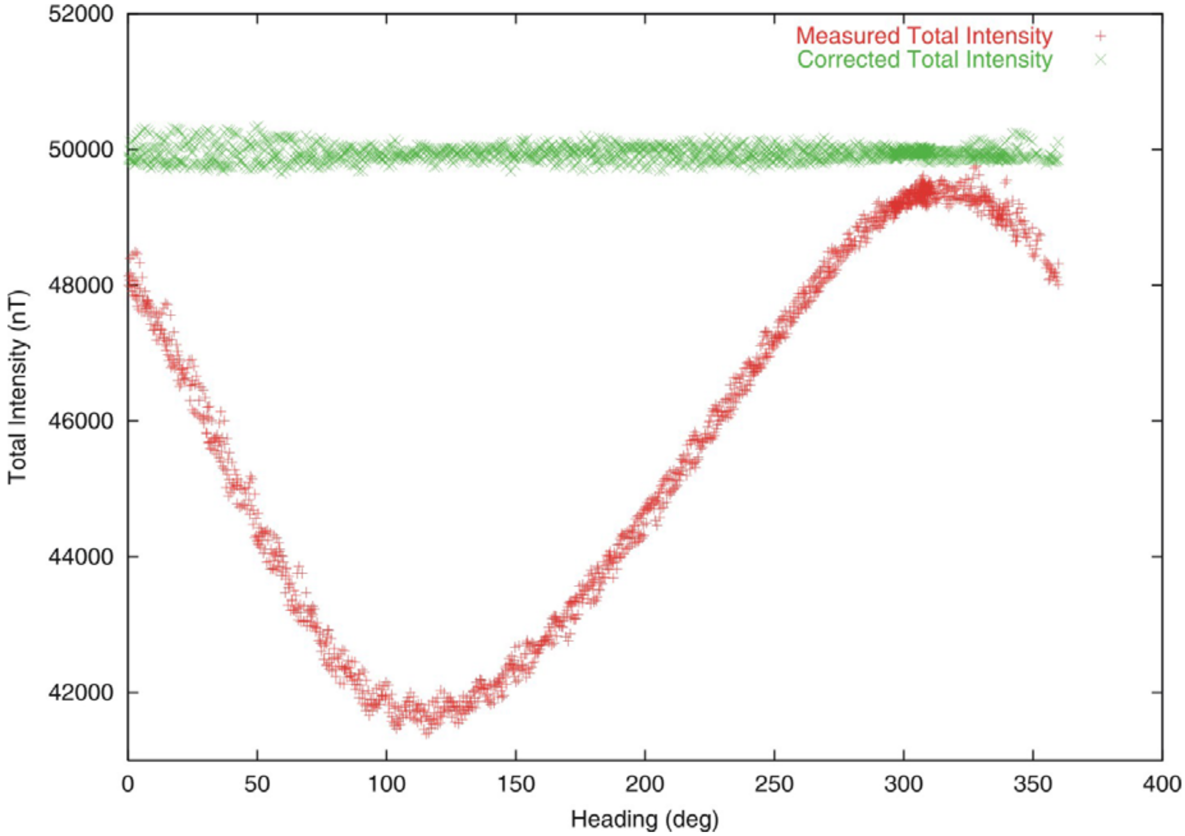
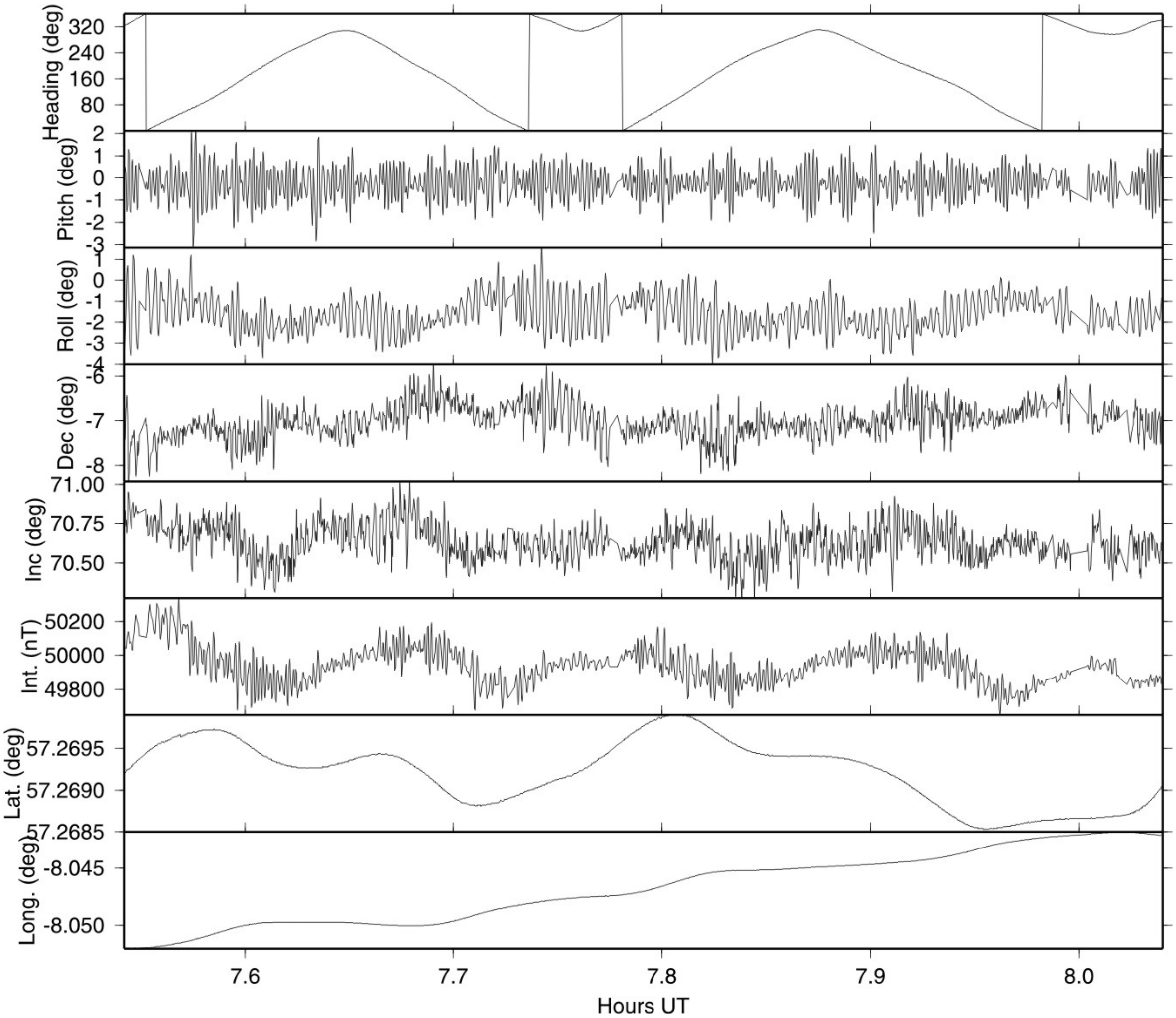



Figure 9 shows the attitude data output from the primary AHRS, our best estimates of the declination, inclination and total intensity, and the position of the vessel in latitude and longitude. Ideally the vessel would not drift during the swings, but this is difficult to control in practice and, as shown, the RRS Discovery drifted by 613 m towards the east and moved by 160 m in latitude during the half-hour when the data were acquired. The vessel did two full 360° swings - one to starboard and one to port. The pitch and roll varied through [-3°, 2°] and [-4°, 1°] respectively. Both estimated declination and total intensity clearly drifted while the vessel moved east. Inclination and total intensity have long wavelength variations that correlate well and seem to follow the displacement in latitude of the vessel. However, these variations may also be interpreted as poor accuracy of the attitude data or failure of the hypothesis of isotropic bulk susceptibility of the vessel. We are inclined to believe that these variations are due to the local crustal field (Figure 7), which is not very well known in this area, combined with weak anisotropy of the vessel susceptibility.

The long wavelength variations aside, the data present very short wavelength variations, apparently due to a poor correction for the vessel signal associated with the pitch and roll. The limitation of the AHRS accuracy for pitch and roll combined with a very large vessel signal is likely to be the source of these variations but again, part of this signal may be due to an anisotropic bulk susceptibility. Although our processing scheme has been successful in reducing the noise due to the vessel that was originally up to 24.1° in declination, 5.6° in inclination and 4622 nT in total intensity, the residual vessel effect in our estimated magnetic field strength and direction is still too large for most applications.

**Figure 9 Attitude data (heading, pitch and roll) given by the primary AHRS during the swings, estimated values corrected for the vessel signal of the declination, inclination and total intensity and vessel position in latitude and longitude.**




Ignoring the vessel displacement during the swings, the measured direction and strength of the inducing field as estimated during this calibration process are given in Table 3 together with their standard deviations (SDs) and the BGGM estimates. The measured inclination is in agreement with the BGGM values and its SD is reasonably small. The vessel displacement during the swing can account for a significant part of the relatively large SDs of total intensity and declination. These apparent discrepancies may also be explained, in part, by weak anisotropy of the vessel susceptibility.

Should there be a constant offset in the AHRS heading output, it will map directly on the declination value, however, such an offset may be determined by reference to the secondary AHRS reference system. In this case, the declination and inclination estimates are -7.365° and 70.516° respectively with associated SDs three times as large as with the primary system. Clearly, due to the noise level, this offset is too small to be detected here. We can also check the dependence of the inclination and declination estimates on the input total intensity value. Adding or subtracting 100 nT to this input value generates a variation in inclination of less than ±0.04° and in declination ±0.001°.

Finally the three components of the vessel remanent magnetic field during the swings, as measured at the magnetometer location, were estimated to be:

$$r_u = 1203 \text{ nT}$$
$$r_v = -3956 \text{ nT}$$
$$r_w = -14378 \text{ nT}$$

where $u, v$ and $w$ are the three orthogonal reference directions of the primary AHRS. These values are large and, with an estimated value of vertical component of the inducing field of 47116 nT, are strongly dependent on the hypothesis of isotropic susceptibility i.e. on the symmetry of the matrix A. Given that the average total intensity vessel signal is of the order of only 4000 nT, the value of the remanent field in the $w$ direction is excessively large which is a strong argument in favour of assuming an anisotropic susceptibility.

**Table 3 Estimated and measured Declination, Inclination and total intensity of the inducing field at the swing site. The total intensity was not measured and was assumed to be 49942 nT**

| | Declination | Inclination | Total intensity |
|---|---|---|---|
| BGGM | -7.410° | 70.795° | 49997 nT |
| Measured | -7.015° | 70.635° | - |
| SDs | 0.369° | 0.113° | 110 nT |

# 7 Conclusions

We took the opportunity of a seismic survey campaign in the North Atlantic to test our magnetometer and recording technique as well as the processing we apply to the data to estimate the vessel deviation field.

The outputs are not completely satisfactory in that we have not been able to correct sufficiently well for the vessel signal in order to have sufficiently accurate estimates of the absolute strength and direction of the geomagnetic field in normal survey conditions. This is primarily due to the noise in our AHRS data set, which was too high for a disturbance field as large as the one generated by the RRS Discovery. The AHRS noise is predominantly large in pitch and roll, but may be averaged out during the swings, leading to reasonably good estimates of the inducing geomagnetic field direction at these swing locations.

It is clear however, that the outputs of the magnetometer are accurate enough for our work despite the very large gradients and values of the vessel field. Our processing technique is efficient in reducing the vessel signal in our data. But the results show weak anisotropy of the vessel susceptibility. However, if we want to take into account this anisotropy, then the $\mathbf{A}$ matrix becomes non-symmetric with a non-zero trace, and we cannot solve robustly for its nine elements with the data in hand.

The less satisfying part of the calibration is the frame-magnetometer calibration done by rotating the frame at Eskdalemuir, and this is partly due to the temperature dependency of the magnetometer. Therefore, for future work, a system for a better temperature control is needed as well as a more accurate AHRS. Because the survey vessel is not able to swing at a given place without drifting, improvements are possible by acquiring the calibration data while the vessel is navigating a figure-of-eight pattern, hence crossing the same geographic position with a different heading.

# References

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