Ocean Engineering 160 (2018) 68–77

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

# Correction of tri-axial magnetometer interference caused by an autonomous underwater vehicle near-bottom platform

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ARTICLE INFO

*Keywords:*
Autonomous underwater vehicle
Three-component magnetometer
Near-bottom magnetic data
Heading correction
Magnetic interference

ABSTRACT

Autonomous underwater vehicles (AUVs) are advanced near-bottom platforms that can be used for magnetometric analysis of the seafloor. However, the vehicle itself can cause interference with the magnetic measurements, which need to be corrected. Here, we derive a functional relation between the magnetic measurements and AUV's heading that is based on the composition and causes of an AUV's near-bottom magnetic anomaly. We set up a method to correct tri-axial magnetometer interference caused by the AUV. Magnetic induction intensity is removed using magnetic data collected during the spinning of the AUV. Connatural magnetic field of the AUV is collected and subtracted by using portable magnetometer. The method performs very well during *QianlongII* AUV experimental tests performed on land and in lake. The method also corrects magnetic data by an autonomous benthic explorer (*ABE*) AUV and yields good results. The effects of main components of *QianlongII* AUV on the magnetic measurement results are analyzed and make sure dominating interference produced by the batteries. That is mitigated using a probe extension pole. Furthermore, excellent survey data and satisfactory correction results are obtained during the AUV sea trials. This verifies the efficacy of the proposed method for correcting tri-axial magnetometer interference caused by AUV.

## 1. Introduction

Autonomous underwater vehicles (AUVs) are a type of deep submergence vehicles (Blidberg, 2001). Generally, they can be readily mobilized for use as a stand-alone vehicle on a wide range of research vessels. They can also be used very effectively in tandem with the mothership, or with other remotely operated vehicles, to improve the efficiency of deep submergence investigations. AUVs can operate in extreme terrains, including volcano calderas and scarps. They are equipped with a standard suite of engineering sensors, such as the PHINS inertial navigation system, forward-looking sonars, and attitude sensors. They can also be mounted with scientific sensors, such as multibeam mapping sonars, sidescan sonars, CTD, optical backscatter sensors, and seafloor photography cameras (Rothenbeck et al., 2013; Yoerger et al., 2006, 2007; Blidberg, 2001).

Multibeam bathymetry and sidescan sonars provide maps and images of seafloor and can cover large geographical areas. However, they only provide surface and shallow crust information. In contrast, geophysical methods offer a means of acquiring data over large areas of seafloor and can collect subsurface structural information (Williams, 2007). Magnetometer is one of the most widely used geophysical equipment used on AUV platforms. It can acquire near-bottom data, which can be used to study geologic structure, basement type, ridge expansion rate, and other seafloor characteristics (Caratori Tontini et al., 2012; Tivey and Dyment, 2010; Tominaga et al., 2008; Fujii et al., 2015, 2016).

However, magnetometers are prone to magnetic disturbances from the surrounding environment, such as interferences caused in the presence of ferromagnetic materials and strong electric currents emanating from the AUV itself and its associated equipment. Traditional proton or optical pumping magnetometers (Lenz and Edelstein, 2006) do not work well in the presence of large interferences caused by the AUV itself. Instead, fluxgate magnetometers (Primdahl, 1979; Ripka and Kaspar, 1998; Auster et al., 2009), which have high sensitivity, stability, and lineation, can acquire three-component and gradient magnetic information in the presence of large interferences or weak magnetic environmental interferences (Lenz and Edelstein, 2006). Currently, three-component fluxgate magnetometers are used to collect magnetic data in many AUVs, such as *ABYSS* AUV (Szitkar et al., 2015), *AsterX* AUV

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https://doi.org/10.1016/j.oceaneng.2018.04.066
Received 29 September 2016; Received in revised form 20 March 2018; Accepted 18 April 2018

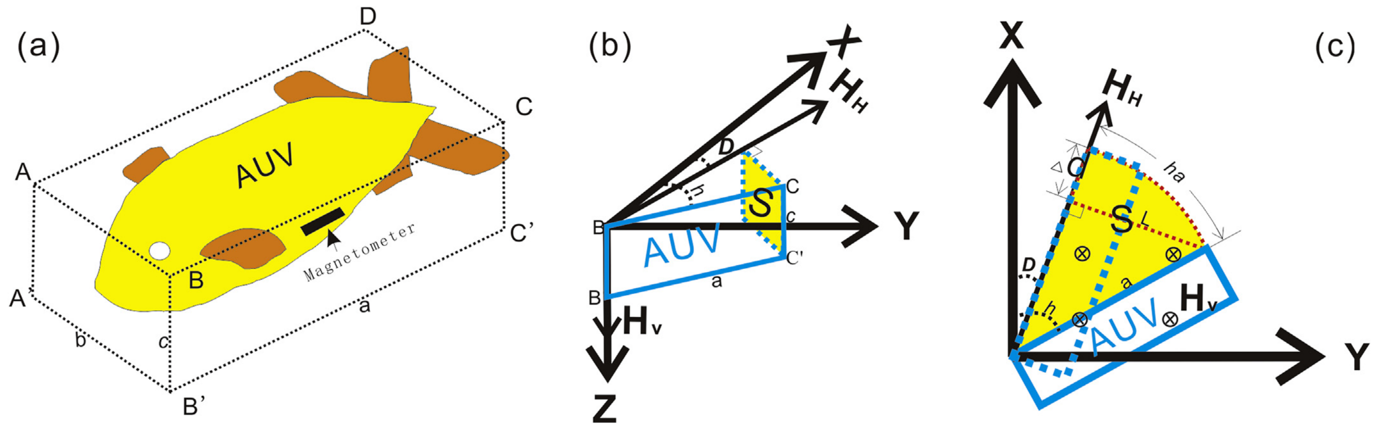


**Fig. 1.** Diagrammatic sketches of the varied relations of the magnetic flux with changes in AUV heading: (a) the AUV structure simplified as a regular hexahedron. Vertices of the hexahedron were denoted as A, B, C, D, A′, B′, C′, and D′ and *a*, *b*, and *c*, corresponding to the size. (b) diagrammatic sketches of the effective area swept by magnetic induction lines of four faces with parallel to $\vec{Z}$. Taking surface $BCC^{'}B^{'}$ for example, its effective area is $ac\cos(h-D)$. Where $H_H$ is horizontal intensity of geomagnetic field, $H_v$ is vertical intensity of geomagnetic field and *D* is geomagnetic declination. (c) is diagrammatic sketches of the corresponding equivalent length and velocity when regarded AUV as a conducting stick. When it cutting the horizontal magnetic induction lines, effective length of conductor is $L = a\sin(h-D)$ and its velocity is $v = \frac{da(1-\cos(h-D))}{dt}$. When it cutting the vertical magnetic induction lines, effective length of conductor is $L = a$ and its velocity is $v = \frac{adh}{2dt}$.

(Szitkar et al., 2016), *Autosub6000* AUV (McPhail et al., 2010), and the autonomous benthic explorer (*ABE*) AUV (Tivey et al., 1997; German et al., 2008).

When using AUV near-bottom platform, information regarding effective magnetic anomalies can only be obtained after correcting for magnetic interferences and then completing the routine processing work. For example, *ABE* AUV produces a field effect on the order of 1100 nT during a spin. However, this field may still vary by up to 300 nT after correction, which is not sufficient enough to obtain accurate data (ftp://ftp.whoi.edu/pub/users/mtivey/mfiles). Therefore, further study of the nature of magnetic anomalies and the associated potential magnetic interferences is required to obtain adequate three-component magnetic data.

## 2. Components of raw near-bottom magnetic data

### 2.1. Outside magnetic interference

The magnetic field at any point on or outward from the Earth's surface comprises magnetic field originating from the Earth's core and crust, along with contributions from external field. The external magnetic field is generally affected only by magnetic diurnal variation, which typically has a daily amplitude variation of approximately 30 nT (Lee et al., 1996), though it may sometimes reach 40–60 nT (Luo et al., 2015). During marine magnetic surveys, the daily variation is usually ignored, as it is difficult to set up an appropriate observation station and the variation is typically well below that of the typical magnetic field anomalies generated by crustal sources. The diurnal variation can also be reduced using data from a nearby geomagnetic station, or if possible, by installing a station on a mooring system. Magnetic storm events can temporarily affect every place on the planet, as well as affect the auroral and equatorial electrojets, which are more localized external disturbances. These disturbances can interfere with data collection during research, as magnetic data would not be available during a magnetic storm.

The effect of magnetic field of the Earth's core is corrected by calculating a correction factor from a function. The most representative function is the International Geomagnetic Reference Field (IGRF), and the independent variables are chosen to be the point location parameters. The crustal magnetic field, including the target geomagnetic anomalies, also include the field of various geological bodies. Therefore, it is difficult to separately obtain the target anomalies. Nevertheless, we can perform an up/downward continuation and reduce the curved surface into a horizontal plane to lessen the effect of non-target objects during processing of the magnetic data. Certainly, with magnetic anomaly data and magnetization of rocks, we can invert the distribution of magnetization and infer or explain the geomagnetic structure of the targets by combining other available survey data.

### 2.2. Platform influence

AUVs, themselves, also contribute to magnetic distortions, which can affect the acquisition of useable magnetic anomaly data. These distortions can be divided into permanent and induced magnetic field effects caused by the vehicle (Leliak, 1961). The permanent magnetization effect is simply the additive magnetic field produced by permanent magnets or electrical currents. Routine reduction of the permanent magnetization effect involves the introduction of an offset in each direction of the three channels of the magnetometer to minimize the deviation between the observations and the corresponding IGRF (Bronner et al., 2013). The magnetization effect is induced by materials that generate their own magnetic field and cause a distortion in the underlying magnetic field in both intensity and orientation. The usual correction method is performed by finding a suitable functional relation between the field intensity and heading angle (Caruso, 2000; Tivey, 1996). For example, the induction field correction equation, $2\pi$ periodic function of heading, for the induced magnetization in *ABE* AUV is

$$H_I^{'} = \frac{\partial H_I}{\partial h} = m\cos(h-D) \tag{1}$$

where $H_I$ is the magnetic induction intensity, $H_I^{'}$ is the variation of $H_I$ with heading ($h$) and is a function of the multiplication factor ($m$), $h$, and declination ($D$) (Williams, 2007).

We have developed a 4500-m AUV, named *QianlongII* AUV, which contains integrated technologies, including hydrothermal anomaly detection, microtopography measurement, video and photographic recording, and magnetic surveying equipment. Therefore, it can be a practical system for deep-sea exploration of mineral resources, such as polymetallic sulfides. Preliminarily, we attempted to correct the magnetic interferences from our AUV using typical methods, but did not obtain good results. For this reason, we began with a theoretical analysis to perform a systematic study of the magnetic interferences caused by the AUV. We then amended the original correction method and performed trials on land, in a lake, and at sea to determine whether the new correction method could be used to obtain satisfactory correction results.