The need for seafloor geomagnetic observatories: the geomagnetic component of the FRENCH program OFM

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Abstract. In this paper, we first describe recent developments in measuring the geomagnetic field. Secondly, the improvement in our knowledge of the magnetic field made possible by the development of ocean bottom observatories (OBO) is discussed.

1 Introduction

Observing the Earth's magnetic field can be regarded as the oldest branch of the modern scientific discipline known as geophysics. In the present day, measuring the magnetic field is more concerned with answering the fundamental questions about the Earth's deep interior and its near-space environment than with practical navigation. The geomagnetic data are of great use in some other geophysical studies, such as decade-period changes in the length-of-day, or the thermal core-mantle interactions.

In this era, when new and exciting satellite missions (Ørsted, CHAMP) will investigate hitherto hidden features of the Earth's magnetic field, the role of existing ground observatories might be questioned: why are new observatories needed and why should they be proposed in difficult locations such as the sea floor? Foremost, the geomagnetic observatory network is the primary source of data in elaborating secular variation models. Additionally, the combined analysis of data from ground stations and satellite missions will drastically enhance the signal-to-noise ratio and the extraction of the various sources of the field, enabling a unique separation of the internal and external parts.

We first describe recent developments in measuring the geomagnetic field. Secondly, the improvement in our knowledge of the magnetic field made possible by the development of ocean bottom observatories (OBO) is discussed. Finally, the inclusion of magnetic instrumentation on a general purpose geophysical ocean bottom platform is investigated.

2 Measuring the Earth's Magnetic Field

Measurements of the geomagnetic field are made in two categories: scalar and vector. Scalar measurements are of the strength of the magnetic field only, and provide no information about its direction. These measurements are commonly made with proton precession magnetometers or caesium vapour magnetometers. The former are typically installed at magnetic observatories, and the latter are used in making survey measurements at sea or by air. Vector measurements provide information about the direction of the Earth's magnetic field, as well as its strength. Such measurements are typically obtained using three orthogonal fluxgate magnetometers which measure the strength of the components of the magnetic field along their individual axes.

The main difficulty in running a magnetic observatory arises from the different nature of absolute and variation measurements. A scalar measurement of the field intensity obtained by a proton magnetometer is absolute: this means it depends only on knowledge of a physical constant (the proton gyro ratio) and a measurement of frequency, which can be achieved with great accuracy (at least 10 ppm). In contrast, a vector measurement made with a fluxgate magnetometer is subject to instrument drift arising from sources both within the instrument (eg. temperature effects) and also the stability of the instrument mounting. Because these measurements are not absolute, they are referred to as "variation" measurements, and the instruments are referred to as "variometers". It is possible to make an absolute measurement of the direction of the geomagnetic field, but this can only be performed with an instrument known as a "fluxgate-theodolite" which requires manual operation and takes about 15 minutes. In a land-based observatory, such absolute measurements are typically made once a week and are used to monitor the drift of the fluxgate variometers. The fluxgate-theodolite measures the direction of the geomagnetic field with respect to the horizontal plane (inclination) and the angle in the horizontal plane between magnetic north and true north (declination). Herein lies the greatest problem in developing an ocean bottom observatory: how to provide the reference to the horizontal and to true north for absolute measurement of the field direction.

Modern land-based magnetic observatories all use similar instrumentation to produce similar data products. For a full description see the Intermagnet Technical Manual (2000). The fundamental measurements recorded are one-minute values of the vector components and of the scalar intensity. The one-minute data are important for studying variations in the geomagnetic field external to the Earth, in particular the daily variation and magnetic storms. Data from a global network of observatories are used to produce the Kp magnetic activity index. From the one-minute data are produced hourly, daily, monthly and annual mean values. It is the monthly and annual mean values that capture the secular variation emanating from the Earth's core. The quality of estimates of secular variation depend critically on the quality of absolute measurements at each observatory, and the same will be true of ocean bottom observatories.

The first magnetic observatories capable of making full vector measurements (ie. direction and intensity) began operation around the world in the mid-19th century, following the encouragement by Humboldt and Gauss to the international community. This was partly a result of the development of the technique of spherical harmonics to model the Earth's magnetic field, the method which is most commonly used today and which is described in the next section. The main limitation in using this technique is the poor distribution of data around the globe. Although the situation is much improved today it is still not ideal, especially in the large ocean areas of the globe, hence the need for ocean bottom observatories.

3 Ocean bottom observatories and modelling

The main problems arising in modelling the Earth's main-field and of its time variation (secular-variation) have been outlined by previous authors (e.g., Cain et al., 1990; Barraclough, 1990; Lowes, 1990, Alexandrescu et al. 1994; Langel, 1987). The spatial and temporal distribution of the observatory data employed in the model derivations is a key-parameter in obtaining a good accuracy. How ocean bottom observatories will contribute to increased accuracy in modelling is discussed below.

A mathematical model to describe the Earth's main field and its secular variation comprises a set of spherical harmonic coefficients (called Gauss coefficients), g_n^m and h_n^m, in a truncated series expansion of a geomagnetic potential function of internal origin.

The geomagnetic coefficients are computed so the magnetic field $\overrightarrow{B}$ fits the data in the least-squares sense (Cain et al., 1967):

$$\widetilde{X} = (A^T W A)^{-1} A^T W M \qquad (1)$$

where M is the column vector of data, X the column vector of Gauss coefficients, A the so-called "geographic matrix", and W the column vector of the weighing coefficients.

A possibility to estimate the accuracy of the model is the use of the so-called covariance matrix, i.e. $V_X = (A^T W A)^{-1}$. In the ideal case, when data are uniformly and densely distributed on the sphere and unit weights are adopted ($W \equiv I$), the covariance matrix V_X is diagonal (all the off-diagonal terms of $A^T A$ have to be zero because of the orthogonality properties of spherical harmonics). The correlation between the Gauss coefficients gives off-diagonal terms in the V_X matrix (the off-diagonality of V_X is then considered as an indicator of the improvement of the actual situation when new observatory sites are installed).

The observatory coverage is dramatically unbalanced between the continental and the ocean areas and between the northern and the southern hemispheres. Even though observatories are proposed for some islands, two problems remain. The first problem arises from the fact that many ocean islands are volcanic and possess strong magnetic gradients. Secondly, there are still many areas of ocean, particularly in the Pacific and the Indian Oceans, where no suitable islands exist.

4 Magnetic instrumentation for the ocean bottom observatories

The construction of a seafloor geomagnetic observatory with the requirements set for an Intermagnet magnetic observatory is complex and must include vector magnetic field measurements with a resolution of 0.1 nT, a dynamic range of 2000 or 6000 nT (depending on geomagnetic latitude), a usable bandpass from DC to 10 s period, a sample interval of 5 s, and long term stability of 5 nT per year. The accuracy requirement is a centered 10 nT spread for 95% of the data. Thermal stability is probably not an issue on the seafloor because the bottom temperature varies at the 10 millidegree level. The requirements for a scalar magnetometer include a resolution of 0.1 nT and an accuracy of 1 nT with a 30 s sample interval. Data logger clock accuracy should be 5 s/month (Chave et al. 1995).

4.1 Major Sensor Components

The major sensors required for a seafloor geomagnetic observatory include a three component vector magnetometer, an absolute field sensor, an absolute direction sensor, and tilt sensors. The first two and last do not require major innovation, while seafloor measurements of absolute direction present new challenges.

The variometer used is a 3 component fluxgate which has a sensitivity of 0.10 nT. Great care is needed to prevent any significant degradation of the sensitivity when confined in a pressure case due to the high level of electronic noise. This technology is adequate to meet the Intermagnet standard. The chief disadvantage to these sensors is the high power requirement (typically, 0.5 watt per component).

Absolute magnetic field measurements may be made using commercially available technologies as well. The simplest and lowest cost approach would utilize a Overhauser scalar magnetometer capable of 0.1 nT absolute accuracy. The sensor must be polarized nearly continuously to yield accurate data, but is easily capable of the requisite 30 s sample interval.

The most serious sensor development effort required for a seafloor observatory is providing an absolute (i.e., celestial) direction reference. A vertical reference is easily obtained using gravity, but the difficulty is obtaining an absolute reference in the horizontal plane. On land, this is provided by optical measurement relative to an astronomical body using a precise clock, but this is clearly not feasible on the seafloor, and some more indirect means must be sought. The required accuracy may be estimated from the Intermagnet specifications; 1 nT in a 50,000 nT geomagnetic field corresponds to 4 seconds of arc, while 5 nT in the same field requires 30-50 second accuracy depending on the local geomagnetic field. This corresponds to absolute angle measurement at the 1 part in 10^5 level. The approach used involves a high precision gyrometer (30" arc) powered every day.

A few ancillary measurements are also required. A vector magnetometer serves as a very sensitive tiltmeter; it is easy to show that 1 microradian of tilt will yield an apparent magnetic signal of order 10 pT at mid-latitudes. Much larger tilts of the seafloor associated with tectonic activity and microseismicity can be expected, and hence it is prudent to independently measure the tilt field and use the resulting data to correct the magnetic variations. This is easily accomplished for tilt about the two horizontal axes where the deflection of a weight relative to the local vertical can be measured optically. The remaining component of tilt (rotation about the vertical axis) is much more difficult to measure due to lack of a reference, but can be considered from the gyrometer repeated measurements. Finally, temperature needs to be monitored to allow detection of thermal effects on the sensors.

5 References

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