Development of an improved geomagnetic reference field of Antarctica

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Abstract
The properties of the Earth's core magnetic field and its secular variation are poorly known for the Antarctic. The increasing availability of magnetic observations from airborne and satellite surveys, as well as the existence of several magnetic observatories and repeat stations in this region, offer the promise of greatly improving our understanding of the Antarctic core field. We investigate the possible development of a Laplacian reference model of the core field from these observations using spherical cap harmonic analysis. Possible uses and advantages of this approach relative to the implementations of the standard global reference field are also considered.

Key words *geomagnetic reference field – spherical cap harmonics – polar regions*

1. Introduction

The accurate estimation of magnetic anomalies requires effective removal of the core and external field components from the magnetic observations. Since continuous geomagnetic records in Antarctica and its surrounding oceans are sparse and not well-distributed, there is a clear need to improve the accuracy of the core field and its Secular Variation (SV) as represented by the International Geomagnetic Reference Field (IGRF) models. In addition, the Antarctic Digital Magnetic Anomaly Project (ADMAP) is working to compile individual surveys into maps at regional and continental scales, incorporating data taken at very different altitudes (from sea-level to satellite) and spectral band-widths. For correctly levelling these different kinds of data, it will be of great help to resort to representing not only the field due to sources at the fluid outer core, but also those longest wavelengths of the crustal field that may overlap the different sectors into which the Antarctic has been divided for compilation purposes (Johnson *et al.*, 1997; Chiappini *et al.*, 1998).

In this short note we therefore consider the possibility of developing a Laplacian core field model based solely on Antarctic geomagnetic observatory and repeat-station data, as well as on data from near-surface and satellite surveys lying south of 60°. For this purpose we recommend the use of Spherical Cap Harmonic Analysis (SCHA) for reasons that will be enumerated in the following sections.

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2. Environment restrictions and data availability

The Antarctic region is, for most of its territory, a desert of ice with temperatures as low as around –90 °C and wind speeds up to 300 km/h. These hostile conditions limit the presence of man and, in turn, most of the capability of installing, running and preserving conventional geomagnetic/geophysical observatories for regular, continuous recording of the geomagnetic field. This situation is more evident in the internal areas, where the more extreme conditions of low temperature and remoteness, greatly reduce the possibility of monitoring good, reliable sites of observations. In addition, some of the observatories, such as those placed on the polar shelf, must be periodically relocated because of the slow but continuous motion of ice. Nowadays, many of the observations are performed by means of automatic instruments that are normally checked only once a year for maintenance and for data transfer. For these reasons, as well as the fact that there is sometimes a lack of frequent absolute observations, it has been difficult to incorporate these stations into the world wide network of standard geomagnetic observatories. Roughly 10 to 15 (fig. 1) observatories have been simultaneously running south of 60° between 1960 and 1994. After this period, the use of Antarctic observatory data in the world wide network decreased drastically because of the lack of timely updated data, and the recent closure of some observatories. In spite of the small number of stations and their spatial distribution that is limited mostly to the coast, the related observations represent a precious ensemble that is important to monitoring the secular variation of this part of the Earth's surface. Figure 2 shows the spatial distribution of Antarctic observatories that were running continuously over part or all of the time span of concern. The latter might be slightly extended backwards to include the International Geophysical Year (IGY), when there was a noteworthy promotion for the deployment of new observatories and an enhancement of the survey activity, especially in the polar regions.

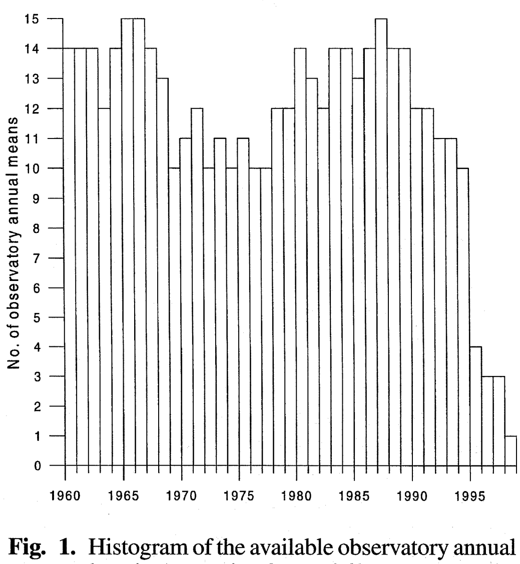

Fig. 1. Histogram of the available observatory annual mean values in Antarctica from 1960 to present. The drastic decrease in the last few years reflects both the lack of timely updated annual means and the recent dramatic increase in the number of observatories suffering operational difficulties or even closure.

Repeat stations in Antarctica are not many and they were often undertaken over areas surrounding observatories, so their utility for augmenting observatory data may be limited. However, in combination with other land surveys that reflect single occupations of sites, they can help to fill in some gaps both in space and time for enhanced reconstruction of the secular variation (see fig. 2).

Data from satellite observations, such as those from Magsat and the POGO series, provide uniform magnetic coverage except for a polar gap of about 5° about the pole. Hence satellite magnetic data will be of inestimable value for modelling the static component of the main field. However, the characteristics of the equipment used are often very different from one mission to another, and the removal of the ionospheric and magnetospheric current contributions is not an easy task. The pending Oersted/Sunsat mission will be of great benefit in improving the model for both internal and external fields.

Other important sources of data for the Antarctic reference field determination are available from marine and aeromagnetic surveys,

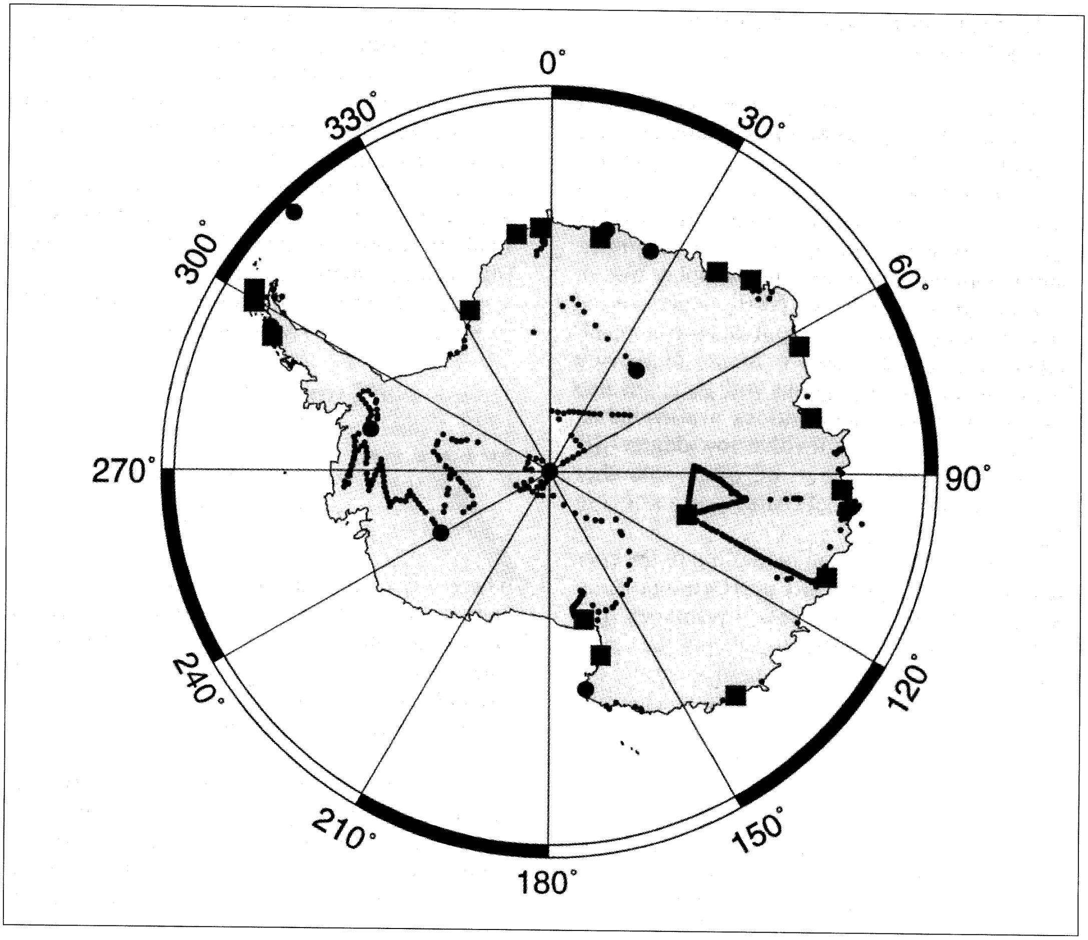

Fig. 2. Distribution of the available land observations in the Antarctic from 1960 onwards. Big circles indicate geomagnetic observatories that closed before 1975, while the squares correspond to those providing annual means after this epoch. Small circles indicate the positions of the survey data, some of which have been re-occupied during the time-span of interest and thus are considered as repeat stations.

including the three-component high-level Project Magnet data (Coleman, 1992). The huge amount of marine and aeromagnetic data available for the Antarctic became clear with the initiation of ADMAP (Johnson *et al.*, 1997; Chiappini *et al.*, 1998). The reader will be able to find elsewhere in this volume many details regarding these magnetic dataset, which are being processed by the ADMAP working group for dissemination to the public as soon as possible.

A further complication for modelling the main field in this region, which is common to all types of data, involves the contamination due to the presence of strong external magnetic fields caused by auroral and magnetospheric currents. An improved local core field model can facilitate better knowledge of the spatial-time characteristics of the external fields that may allow us to take them more completely into account in reducing magnetic data for anomalies.

3. Why a regional field model and why SCHA?

In geomagnetism, the use of regional models over global models has several advantages. For example, the determination of global models needs measurements distributed all over the world that are unevenly distributed and difficult to update in a timely manner. Over a limited region, a global model may also display bias in some components and thus poorly represent the corresponding SV field. Both facts can result because any global model is forced to provide the best fit not only to regions with data, but also to those where no observations are available. Finally, global models involve low-degree SH truncated expansions that are often smoother than the observed regional characteristics of core origin.

In general, for regional modelling of the core field, the use of Spherical Cap Harmonic Analysis (SCHA) has some clear advantages. For example, SCHA can take into account the three-dimensional distribution of data in spherical coordinates in a way that is analogous to classical spherical harmonic analysis. SCHA considers the solution of Laplace's equation in a restricted-spherical cap region.

The application of SCHA is particularly well suited in our specific case where the Antarctic study region involves an actual spherical cap region with data taken at different altitudes.

4. Basic principles of Spherical Cap Harmonic Analysis (SCHA)

SCHA was first introduced by Haines (1985). It can represent over a spherical cap of half-angle θ_0 the internal potential $V(\theta, \lambda, r)$ of the geomagnetic field as a 3D expansion of Spherical Cap Harmonics (SCHs) in colatitude θ and longitude λ, which are both referred to a coordinate system with pole at the centre of the spherical cap surface, so that:

$$V(\theta, \lambda, r) = a\sum_{k=0}^{\infty}\sum_{m=0}^{k}(a/r)^{n_k}$$

$$(G_k^m \cos m\lambda + H_k^m \sin m\lambda)\, P_{n_k}^m(\cos\theta)$$

where G_k^m and H_k^m are the coefficients of the expansion; the $P_{n_k}^m(\cos\theta)$ are Legendre functions with integer order m and, in general, real degree $n_k(m)$, which in turn depends on m. Analogously to the global expansion in classical spherical harmonics, the terms $P_{n_k}^m(\cos\theta)\cos m\lambda$ and $P_{n_k}^m(\cos\theta)\sin m\lambda$ are called the *spherical cap harmonics*. The potential as expressed above satisfies Laplace's equation over the spherical cap region of study.

The functions $P_{n_k}^m$ of the potential satisfy the following boundary conditions:

$$dP_{n_k}^m(\cos\theta)/d\theta\,|_{\theta=\theta_0} = 0$$

for k-m = even, and for k-m = odd

$$P_{n_k}^m(\cos\theta_0) = 0,$$

where k is an integer index that, for a given m, enumerates all the roots n_k satisfying the above conditions alternatively. These boundary conditions can be heuristically explained as a local extension of the conditions of classical spherical harmonic analysis at the equator (De Santis, 1991).

Analogous to classical spherical harmonic analysis, the spherical cap representation is characterised by a minimum wavelength of $2\pi a/n_k$, which can be practically approximated by $4\theta_0 a/k$. Thus, the immediate advantage of using SCHA with respect to classical spherical harmonic analysis is that we can represent the same details of the geomagnetic field in the study region with a fewer number of coefficients.

5. Modelling secular variation

The simplest way to obtain a combined model of the main field and its SV for a given time span is to first produce a model of the SV. This model may be developed by simply taking the first-time derivatives of the field as first-differences of the annual means, thereby obtaining a set of G_k^m and H_k^m in units of nT/year that in turn are expressed as appropriate series expansions in time. This SV model may afterwards be used to update all the main field data to a common epoch and carry out another analysis for the fixed field (Haines and Newitt, 1986; Newitt and Haines, 1989; Torta *et al.*, 1993). However, in Antarctica the external fields are very strong and their effect on the annual means can be very high, so reliable SV can be better estimated from the geomagnetic field observed at very quiet periods of magnetic activity. Some scheme of a suitable choice of these quiet values will be investigated.

The irregular distribution in space and time of the available observatory and repeat-station data in Antarctica suggests representing SV by modelling main-field differences – *i.e.*, by taking differences relative to the means over the data at each observatory or repeat-station location (Haines, 1993). This method appears to be as valid for unequally spaced data as it is for the very few cases of equally spaced observatory data over the time-span since 1960. On the other hand, it allows all data sets to contribute to the determination of the SV, not just those from the fortunate cases where data have been obtained repetitively at the same location. A modification to the original SCHA modelling software of Haines (1988) has made it possible to include scalar observations in the analysis (Haines and Newitt, 1997), and thus to make use of the coverage offered by satellite, airborne, or marine total field surveys not only for the main field modelling, but also for its secular variation, which may be modelled simultaneously by this technique.

6. Possible uses and advantages of a reference field for Antarctica

An improved reference field for Antarctica will enhance the reduction and merging geomagnetic surveys. It would provide better accuracy, both in terms of the main field and its SV, with respect to the existing global models that at present are poorly constrained. It can also be very useful for developing new candidates for the next IGRF. Finally, it could help define reliable spectral properties of the internal geomagnetic field at a higher degree and order than has been possible up to now.

7. Future plans and conclusions

The production of a regional geomagnetic reference filed model over the Antarctic seems possible that will be significantly more accurate than the IGRF. The collection and validation of data will be a central task that must be undertaken, and any support from the scientific community will be very welcome and appreciated. Further improvements may also focus on the inclusion of fields from ionospheric and magnetospheric sources. Their accurate knowledge is a very important factor in Antarctica, from the point of view of the reduction of magnetic surveys in, or close to, the auroral and polar cap zones, where the geomagnetic activity is greatly enhanced. This approach has already been attempted at a global scale (Langel *et al.*, 1996; Sabaka *et al.*, 1997) and has shown promise in applications, such as isolating north-south trending anomalies of lithospheric origin in satellite magnetometer data containing strong external field components (Purucker *et al.*, 1997).

Acknowledgements

The observatory, land survey, and repeat station data were made available for this study from the World Data Centre C1 for Geomagnetism (Edinburgh, U.K.).

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