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A New Geomagnetic Field Model for Southern Africa Based on 2005 Ground Survey Data

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Abstract

Geomagnetic field observations over southern Africa, including countries like South Africa, Namibia, and Botswana, were conducted during October and November 2005 as part of a collaborative project, called COMPASS (COmprehensive Magnetic Processes under the African Southern Sub-continent) between the Hermanus Magnetic Observatory (HMO) in South Africa and the GeoForschungsZentrum Potsdam (GFZ) in Germany.

For this purpose some 40 repeat stations were identified, separated by distances ranging from 300 till 400 km. These stations form part of a network of 75 repeat stations, established by the HMO during the last 60 years, and visited at regular intervals of 5 years till 2000. Due to the rapid secular variation change over this area, it was decided to conduct annual surveys at a reduced number of repeat stations. Therefore, between 2000 and 2004 surveys were conducted at a total of 12 stations on an annual basis. This did however not allow for good spatial resolution, hence the increased number of stations in 2005. For the field survey of 2005 the stations were also selected to form two independent sets of 20 beacons each, enabling one to visit these at alternative years respectively. During this campaign 2 teams, consisting of both HMO and GFZ observers, using similar DI Flux theodolites and fluxgate variometers, gathered geomagnetic field data over southern Africa.

Results obtained from this field survey, together with information from the 3 continuously recording magnetic observatories in southern Africa at Hermanus, Hartebeesthoek and Tsumeb, have been used to model the main geomagnetic field, employing a polynomial approach.

1. Introduction

The magnetic field, produced in the core by a self-consistent dynamo mechanism and also known as the “main field”, has a magnitude of approximately 60,000 nT in the polar regions, and decreases to values less than 20,000 nT in the South Atlantic Anomaly region. Observations of the geomagnetic field started in the nineteenth century and today approximately 150 observatories around the globe are recording the field on a time scale of 1 minute and shorter. These observations are crucial in understanding the underlying mechanisms responsible for the generation of the core field, but in particular the long time series are vital to understand the evolutionary behaviour of the field in various parts of the world.

In order to better understand the mechanisms underlying the generation of the Earth's magnetic field, it is desirable to have as long a record as possible of the evolution of the field. The evolution of declination (the angle between the geographic and magnetic north directions) and inclination (the angle of the magnetic field with respect of the horizontal direction) of the magnetic field have been measured over many centuries (Alexandrescu *et al*. 1996, Mandea 2000). In southern Africa, the Hermanus Magnetic Observatory (HMO) has been executing geomagnetic repeat surveys on a routine basis for nearly 50 years. These surveys normally include countries such as South Africa, Namibia, Zimbabwe and Botswana and have been conducted at regular intervals of 5 years till 2000 at almost 70 positions. However, due to the rapid change of the geomagnetic field in this region, it was decided to conduct field surveys on an annual basis, but at a few selected repeat stations. It was therefore decided to visit 10 selected repeat stations at annual intervals for 2003 and 2004. The experience gained from these surveys has shown that the limited number of stations over the Southern African region is insufficient to accurately model the secular variation due to the increasing temporal and spatial gradients. A better spatial resolution, however, demanded an increase in the density of the repeat stations. In 2005 a total of 40 stations were selected for a survey campaign. At 34 stations it was possible to obtain good quality results (Fig. 1).

Results obtained during this field survey were used to derive mathematical models of the main geomagnetic field components measured using polynomials that can be expressed as a function of latitude and longitude. In this publication we present modelling results for declination (D), horizontal component (H), vertical component (Z), as well as total field (F).

2. Data Collection and Field Surveys

Continuous recording of geomagnetic field variations is conducted at Hermanus (34º 25.5' S, 19º 13.5' E), Hartebeesthoek (25º 52.9' S, 27º 42.4' E) and Tsumeb (19º 12' S, 17º 35' E). All these observatories comply with INTERMAGNET standards. The primary instrument for recording of magnetic field variations is the FGE fluxgate magnetometer, manufactured by the Danish Meteorological Institute in Copenhagen, Denmark. This instrument is based on three-axis linear-core fluxgate technology, optimised for long-term stability and records the components H, D and Z. An Overhauser-type magnetometer further provides absolute total field information, while baselines for the other components are obtained using a DI Flux theodolite.

For field survey purposes, field stations are marked by concrete beacons, ensuring that all observation points are exactly reoccupied during surveys. Most measurements are taken on a standard 1.2 m pillar, while in a few cases observers had to use a tripod mounted above a clearly marked shorter beacon. The field survey of 2005 was separated into three different sectors. At first a survey was done by only HMO field surveyors, then 2 independent teams, each consisting of a staff member from HMO and GFZ, conducted a simultaneous field survey in southern Africa. The repeat stations visited during the 2005 field survey campaign can be seen in Fig. 1. The positions with circles were found not suitable for field survey measurements. Mostly it was a case that the region was no more magnetically quiet, or that the observation pillar was destroyed due to urban expansion projects. A DI fluxgate magnetometer was used as primary instrument during field surveys to obtain values of D and I, while an Overhauser magnetometer delivered values of total field intensity (F). Corrections for diurnal variation and other disturbing effects were made by comparing field station observations with magnetic data recorded on site with a LEMI suspended tri-axis fluxgate instrument. This proved to be a vast improvement by using magnetic observatories, sometimes a distance of more than 300 km away (see Korte *et al*. 2007, this volume).

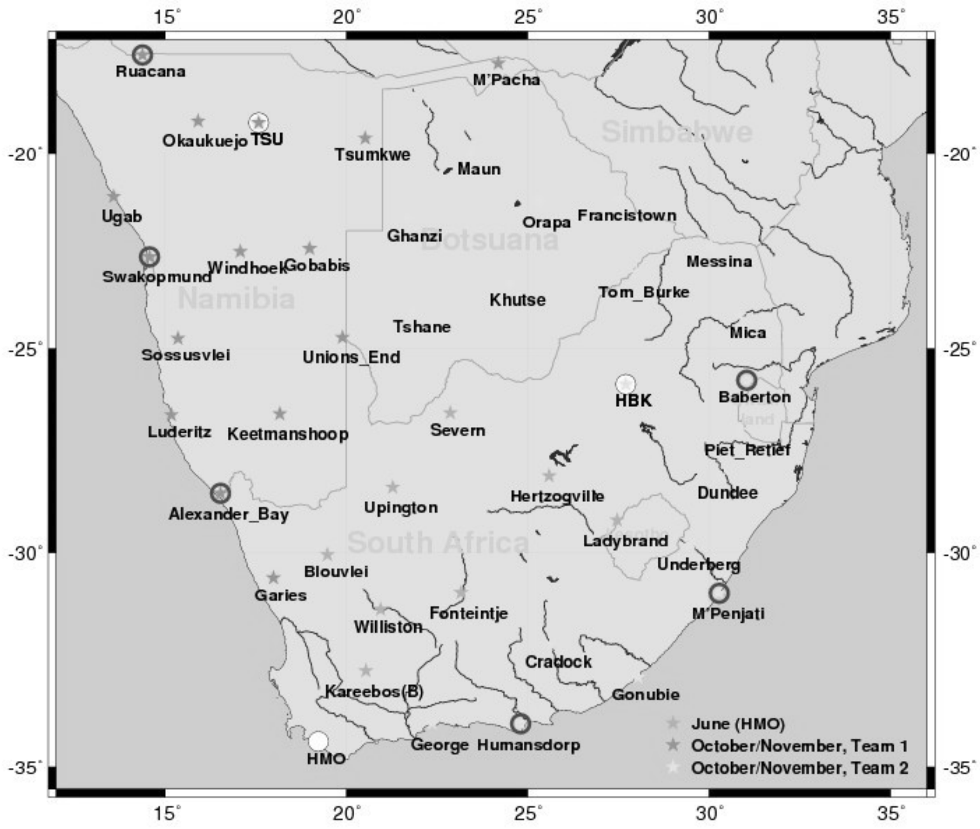

Fig. 1. Map of distribution of repeat stations over the Southern African region, showing the locations visited by the different field survey teams.

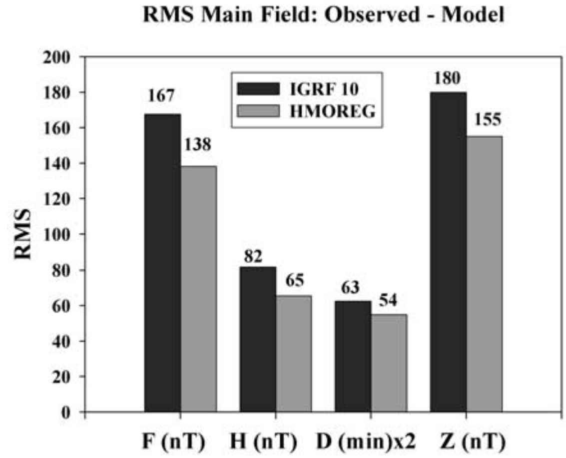

Fig. 2. Comparison of RMS differences between the IGRF10 global field model, the regional model for southern Africa, HMOREG, and field survey measurements. Declination D is scaled up by a factor of 2 in order to match the scale of the bar chart.

3. Regional Geomagnetic Field Modelling over Southern Africa

Over the past few years since 2000, satellite data have been used extensively to model the main field over southern Africa, especially to obtain information over areas not accessible by ground survey teams, like the surrounding ocean areas. Models derived in this way proved to be superior in resolution as well as accuracy to global field models when compared with ground observations (Kotzé 2001). On the other hand, however, ground magnetic field measurements have been exclusively used to derive secular variation models for southern Africa (Kotzé 2003). The field survey conducted in 2005 enabled a polynomial-based main field regional model, called HMOREG. A statistical comparison between these models and IGRF 10 for each field component can be seen in Fig. 2. The models derived for each individual component were based on third degree polynomials as a function of latitude and longitude, with 10 statistically significant coefficients for each magnetic field component modelled:

$$\text{Comp} = A + BX^3 + CYX^2 + DXY^2 + EY^3 + FX^2 + GXY + HY^2 + IX + JY$$

where: X = 26 – Latitude; Y = 24 – Longitude; Comp = Main field component (F, H, D, Z); A–J = coefficients derived from field survey data using least squares fit.

As observatory data, in general, are more accurate than repeat survey data, because of better baseline control and because seasonal and other short-term variations are more effectively removed by using annual means, we introduced weighing factors for both observatory and repeat station secular variation data in a ratio 1:0.7 in the least-squares solution. This ratio was determined by minimizing the RMS difference between model fits and survey data. There were 96 vector differences from 32 repeat stations and 9 vector differences from the 3 observatories, providing a total of 105 data values for the present time interval. A regional main field model for epoch 2005.5 was subsequently derived. The least-squares routine used to fit the data was the stepwise regression procedure described by Efroymson (1960), which has the ability of both entering and removing variables at given levels of statistical significance.

Results obtained by modeling the field survey observations as obtained during the 2005 field survey of southern Africa can be seen in Figs. 3, 4, and 5. A third degree polynomial was used to model the geomagnetic field data.

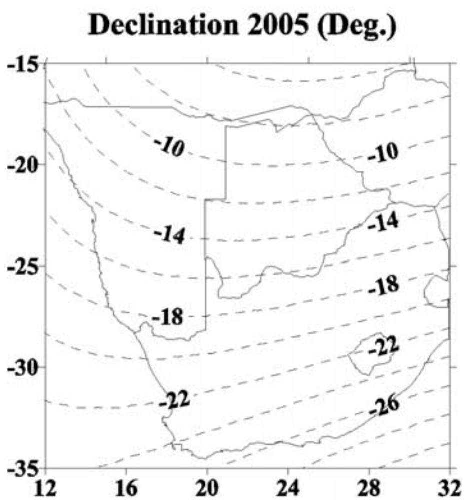

Fig. 3. A contour plot showing the declination for southern Africa as determined by a third degree polynomial fit to field survey data of 2005.

4. Conclusions

The dynamic variation of the magnetic field as observed in southern Africa (Kotzé 2003) necessitates a dense array of suitable ground-based observations for this region with field surveys conducted at regular intervals, preferably on an annual basis.

Results obtained by modelling the declination for 2005 over southern Africa revealed an extremely steep spatial gradient, ranging from almost 26 degrees west of true north in the southern part, to almost 10 degrees west of true north in the northern part. This can clearly be seen in Fig. 3. In comparison to previous field surveys, this pattern is indicative of a growing gradient in the orientation of the geomagnetic field of southern Africa in a north-west to south-eastern direction. The pattern displayed by the horizontal field component H in Fig. 4, clearly indicates that the sub-continent is under the influence of a strong spatial gradient, ranging from 11,000 nT in the south-west to 15,000 nT in the north-western part of the region. This weak H-component in the south-western part of southern Africa can be ascribed to the influence of the South Atlantic Anomaly. As a result, the X-component is anomalously small (Jackson *et al*. 2000). This behaviour is confirmed by the observed pattern for F as displayed in Fig. 5, showing a large spatial gradient from north to south. In the south-western part of the sub-continent the total field is almost 26,000 nT, whereas over the northern part of the region the field is almost 30,000 nT.

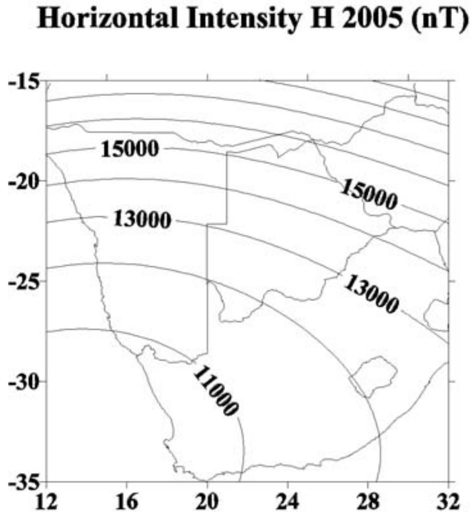

Fig. 4. A contour plot showing the characteristics of the horizontal field component H as modelled by a third degree polynomial using 2005 field survey data.

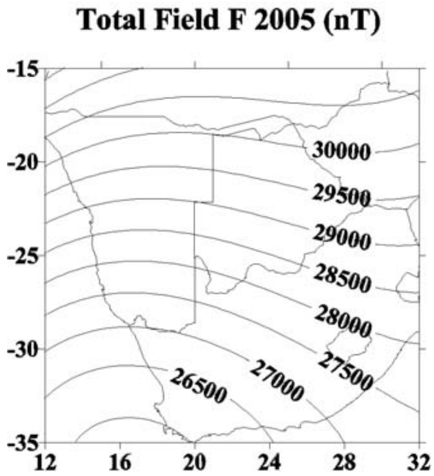

Fig. 5. A contour plot exhibiting the spatial characteristics of the total field F after modelling the field survey measurements of 2005 by means of a third degree polynomial.

Since the first magnetic field measurements started in the nineteenth century, a continuous decrease of the Earth's magnetic dipole moment has been observed. The change in the field strength is, however, not evenly distributed over the globe. In particular, the most rapid decrease of the core field is observed in the Southern Atlantic region. In this regard southern Africa provides an ideal opportunity to study these geomagnetic field changes, as shown in the field survey done in 2005. Since the establishment of the Hermanus Magnetic Observatory in South Africa in 1941, the total field intensity has decreased by 20%, which is greater than decreases observed at any other magnetic observatory.

More interestingly, the growth and position changing of patches of the reverse flux under South African region, from 1840 onwards, can be responsible for changes in dipole moment. Recently, Gubbins *et al*. (2006) showed, by separating contributions of the two hemispheres in the change of axial dipole (g_1^0), that most of the dipole intensity diminishing has come from the Southern Hemisphere. The recent satellite-based models, like CHAOS (Olsen *et al.* 2006), confirm the behaviour of reverse flux patches below southern Africa. These reverse flux patches are likely linked to the expulsion of toroidal flux, which seems to be during the last recent decades, in an active period of expulsion through the core surface.

Moreover, it has been shown recently (Dormy and Mandea 2005) that patches of intense secular variation appear in the South Atlantic hemisphere. It is therefore of the utmost importance to conduct field surveys similar to this one in 2005 in order to obtain data for the compilation of models of fluid flow at the top of the Earth's core which seem to play a key role in the present behaviour of the geomagnetic field of southern Africa.

The IGRF 10 global field model and the newly-derived polynomial models based on the field survey data of 2005 were statistically compared for each component with the survey measurements. Based on root-mean-square differences, for certain components the improvement obtained is almost 20%, as shown in Fig. 2. However, even better improvements (more than 30%) can be obtained when using spherical cap modelling techniques to model satellite data over southern Africa (Kotzé *et al.* 2001). As a next step we intend to integrate satellite magnetic field measurements with ground observations and then use spherical cap modelling to obtain a geomagnetic field model for this region.

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