Studying Antarctica from a magnetic point of view

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1. Importance of crustal fields
2. Magnetic observatories
3. Main field studies
4. Crustal field compilations
5. Regional surveys
Antarctica

- Coldest: -89°C at Vostok
- Highest: average elevation 2,500 meters
- Windiest: 375 km/h at Dumont D’Urville
- Driest: average precipitation < 50 mm/year
- Tallest: 4,776 meters deep in Wilkes Land
Crustal Magnetic Field

Structure and dynamic evolution of the mid-ocean ridge system and oceanic crust

Geological and tectonic studies of the continental crust

Magnetic monitoring of geological hazards (active faults, volcanoes)

Integration of magnetic anomaly data with gravity, seismic, geochemical, remote sensing, geological, and heat flow data
König and Jokat, JGR, 2006
Antarctic Digital Magnetic Anomaly Project
Near-surface survey coverage

Golynsky et al., BAS pub., 2001
## Components of the Magnetic Field

<table>
<thead>
<tr>
<th>Constituent Field</th>
<th>Location of Source</th>
<th>Mean Intensity (Maximum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main</td>
<td>Outer core</td>
<td>50,000 nT (70,000 nT)</td>
</tr>
<tr>
<td>Local</td>
<td>Crust (upper mantle?)</td>
<td>100 nT (10^5 nT)</td>
</tr>
<tr>
<td>Regular Storm</td>
<td>Magnetosphere</td>
<td>150 nT (500 nT)</td>
</tr>
<tr>
<td>Irregular storm</td>
<td>Ionosphere and magnetosphere</td>
<td>100 nT (200 nT)</td>
</tr>
<tr>
<td>Diurnal Variation</td>
<td>Ionosphere</td>
<td>50 nT (200 nT)</td>
</tr>
<tr>
<td>Induced</td>
<td>Crust, upper mantle, and oceans</td>
<td>½ of above three fields</td>
</tr>
</tbody>
</table>
How to combine all these surveys?

\[ \mathbf{B} (\mathbf{r}, t) = \mathbf{B}_m (\mathbf{r}, t) + \mathbf{A} (\mathbf{r}) + \mathbf{D} (\mathbf{r}, t) + \mathbf{\epsilon} (t) \]

- Main Field
- Crustal Field
- Measurement error
- Magnetospheric, ionospheric, and induced Fields

*International Geomagnetic Reference Field*

... sometimes it does not work
Long-wavelength contamination of aeromagnetic survey compilations

Survey A (t0)       Survey B (t1)

Zero-levels after core-field correction & tie-line corrections

Adjustments to avoid edge mismatches

False long-wavelength anomaly

Ravat et al., The Leading Edge, 2003
Chiappini et al., Tectonophysics, 2002

An improved main field reference model for Antarctica is needed
Antarctic Observatory Data

Spatial Distribution

Temporal Distribution

Annual means from the WDC for Geomagnetism in Edinburgh, march 2007
Variometer

• GEOMAG SM90R Overhauser magnetometer at the center of a pair of dual axis Helmholtz coils (BGS)
• Minute values, recording continuously since December 1996

Absolute Measurements

• Elsec 810A D/I-fluxgate on a Zeiss 015B amagnetic theodolite
• Null-field procedure
• Elsec 820A proton precession magnetometer for F
• Observations limited to Austral summer
<table>
<thead>
<tr>
<th>Satellite</th>
<th>Date</th>
<th>Altitude (km)</th>
<th>Inclination</th>
<th>Local Time</th>
<th>Instrumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>OGO-2</td>
<td>Oct 1965 to Sep 1967</td>
<td>413 – 1510</td>
<td>87°</td>
<td>All local times</td>
<td>Rubidium (scalar)</td>
</tr>
<tr>
<td>OGO-4</td>
<td>Jul 1967 to Jan 1969</td>
<td>412 – 908</td>
<td>86°</td>
<td>All local times</td>
<td>Rubidium (scalar)</td>
</tr>
<tr>
<td>OGO-6</td>
<td>Jun 1969 to Jul 1971</td>
<td>397 – 1098</td>
<td>82°</td>
<td>All local times</td>
<td>Rubidium (scalar)</td>
</tr>
<tr>
<td>Magsat</td>
<td>Nov 1979 to May 1980</td>
<td>325 – 550</td>
<td>97°</td>
<td>06:00 / 18:00</td>
<td>Fluxgate (vector) and Cesium (scalar)</td>
</tr>
<tr>
<td>Ørsted</td>
<td>Feb 1999 to present</td>
<td>620 – 850</td>
<td>96°</td>
<td>All local times</td>
<td>Fluxgate (vector) and Overhauser (scalar)</td>
</tr>
<tr>
<td>Champ</td>
<td>Jul 2000 to present</td>
<td>300 – 460</td>
<td>87°</td>
<td>All local times</td>
<td>Fluxgate (vector) and Overhauser (scalar)</td>
</tr>
</tbody>
</table>
Quiet-time Satellite Data over Antarctica
Geomagnetic potential over the Sphere
**SPHERICAL HARMONIC ANALYSIS**

Spherical Harmonic analysis of the Earth’s magnetic field by means of Legendre Polynomials and Fourier series.

Geomagnetic potential over a Spherical Cap
**SPHERICAL CAP HARMONIC ANALYSIS**

Regionalization of the global model for spherical cap by means of non integer Legendre polynomials and Fourier series.
SPHERICAL HARMONIC ANALYSIS

\[ \nabla^2 V = 0 \quad V_i(r, \theta, \phi) = a \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left( \frac{a}{r} \right)^{n+1} \left\{ g_n^m \cos m\phi + h_n^m \sin m\phi \right\} P_n^m(\cos \theta) \]

\[ X \equiv -B_\theta = \frac{1}{r} \frac{\partial V}{\partial \theta} \quad Y \equiv B_\phi = \left( \frac{1}{r \sin \theta} \right) \frac{\partial V}{\partial \phi} \quad Z \equiv -B_r = \frac{\partial V}{\partial r} \]

SPHERICAL CAP HARMONIC ANALYSIS

\[ V(r, \theta, \phi, t) = a \sum_{k=0}^{K} \sum_{m=0}^{k} \left( \frac{a}{r} \right)^{n_k(m)+1} P_{n_k}^m(\cos \theta) \cdot \sum_{l=0}^{L} (g_{k,l}^m \cos m\phi + h_{k,l}^m \sin m\phi) \cdot t^l \]

\[ K, L : \text{maximum index and degree of spatial and temporal expansions} \]

\[ g_{k,l}^m, h_{k,l}^m : \text{coefficients of the model} \]

\[ P_{n_k(m)}^m(\cos \theta) : \text{associated Legendre functions of integral order } m \text{ but usually nonintegral degree } n_k(m), \text{ determined to satisfy alternatively the following boundary conditions:} \]

\[ \left. \frac{dP_{n_k(m)}^m(\cos \theta)}{d\theta} \right|_{\theta=\theta_0} = 0, \quad k - m = \text{even} \quad P_{n_k(m)}^m(\cos \theta_0) = 0, \quad k - m = \text{odd} \]
### Fit to Observatory Data

<table>
<thead>
<tr>
<th>Model</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARM</td>
<td>678</td>
<td>612</td>
<td>1359</td>
<td>1399</td>
</tr>
<tr>
<td>IGRF-9</td>
<td>694</td>
<td>600</td>
<td>1372</td>
<td>1411</td>
</tr>
<tr>
<td>CM4_{internal}</td>
<td>690</td>
<td>611</td>
<td>1365</td>
<td>1403</td>
</tr>
</tbody>
</table>

### Fit to Satellite Data

<table>
<thead>
<tr>
<th>Model</th>
<th>OGO-2</th>
<th>OGO-4</th>
<th>OGO-6</th>
<th>Magsat</th>
<th>Champ</th>
<th>Ørsted</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARM</td>
<td>22.9</td>
<td>13.4</td>
<td>11.4</td>
<td>13.2</td>
<td>9.8</td>
<td>9.4</td>
</tr>
<tr>
<td>IGRF-9</td>
<td>21.9</td>
<td>21.7</td>
<td>22.5</td>
<td>14.7</td>
<td>19.0</td>
<td>19.7</td>
</tr>
<tr>
<td>CM4_{internal}</td>
<td>16.6</td>
<td>22.3</td>
<td>22.2</td>
<td>21.4</td>
<td>24.8</td>
<td>24.5</td>
</tr>
<tr>
<td>CM4_{int+ext}</td>
<td>6.3</td>
<td>5.8</td>
<td>5.3</td>
<td>3.7</td>
<td>4.6</td>
<td>3.3</td>
</tr>
</tbody>
</table>
Fit to Secular Variation

<table>
<thead>
<tr>
<th>Model</th>
<th>RMS X (nT/year)</th>
<th>RMS Y (nT/year)</th>
<th>RMS Z (nT/year)</th>
<th>RMS F (nT/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGRF-9</td>
<td>36.1</td>
<td>38.1</td>
<td>49.6</td>
<td>51.6</td>
</tr>
<tr>
<td>CM4</td>
<td>31.3</td>
<td>34.7</td>
<td>43.8</td>
<td>45.5</td>
</tr>
<tr>
<td>ARM</td>
<td>28.2</td>
<td>32.6</td>
<td>35.3</td>
<td>35.4</td>
</tr>
</tbody>
</table>
### Fit to Ground Data not used in the model

Georg von Neumayer Observatory (-70.617°S, 351.633°E)

<table>
<thead>
<tr>
<th>Model</th>
<th>RMS F (nT)</th>
<th>Mean Secular Variation (nT/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGRF-9</td>
<td>53.0</td>
<td>-107.1</td>
</tr>
<tr>
<td>CM4</td>
<td>51.1</td>
<td>-97.5</td>
</tr>
<tr>
<td>ARM</td>
<td>12.7</td>
<td>-102.6</td>
</tr>
<tr>
<td>Real</td>
<td></td>
<td>-108.9</td>
</tr>
</tbody>
</table>

GVN

ARM

CM4

IGRF-9

RMS F (nT)

Model
ARM Magnetic Field Maps

2005.0
Altitude 50 km, grid interval 50 km
Amplitude range ± 300 nT

SCHA-Modeling of ADMAP

Mean difference 9.2 nT
σ = 8.8 nT
Δ_{max} = 84.5 nT
ρ = 0.95

30° Spherical Cap
λ_{min} = 221 km
Altitude 5 km, grid interval 50 km
Amplitude range ± 1000 nT

SCHA-Modeling of ADMAP

30° Spherical Cap
$\lambda_{\text{min}} = 111 \text{ km}$

Mean difference 43 nT
$\sigma = 42 \text{ nT}$
$\Delta_{\text{max}} = 540 \text{ nT}$
$\rho = 0.85$
Magnetic anomaly data not in ADMAP compilation
GEOIMAG survey
2003/2004 campaign

1. To characterize from a magnetic point of view the Northern part of the Terror Rift (Ross Island, Erebus volcano, and associated volcanic structures)

2. To develop a high-resolution aeromagnetic survey over the McMurdo Sound related to the ANDRILL international project
INGV AIRBORNE GEOPHYSICAL EQUIPMENT

Optically pumped Cesium Magnetometer
AGIS acquisition system: Magnetic Field data + GPS + laser altimeter + Pilot Guidance Unit + video recording system
Also: DGPS + magnetometric base station + radar altimeter

Aerodinamical bird (left) containing the cesium magnetometer (right)
AGIS acquisition system
High-altitude surveys over Ross Island and McMurdo Sound

Twin Otter aircraft, 30 hours, 1500 - 5000 m
High-resolution, low-altitude survey over McMurdo Sound

Squirrel helicopter, 22 hours, 100 m
The study of the crustal field at all scales:

- Local (observatories)
- Regional (surveys)
- Continental (compilations)

constitutes a powerful tool to improve our knowledge of the geology and tectonic history of our planet