EARTH'S MAGNETIC FIELD

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Summary

The geomagnetic field has its main source in the fluid outer core of Earth. Near the surface of the planet it is observed to vary in space and in time on a huge range of scales. These variations result from processes in regions ranging from the deep interior of Earth, the crust, ionosphere, magnetosphere, all the way to the Sun. Observing Earth's magnetic field provides valuable insights on all these processes. These observations are made by geomagnetic observatories, extensive surveys made on land, at sea, and from aircraft and satellites, and from magnetic properties of rocks.

1. Introduction

Earth's magnetic field is generated in the fluid outer core by a self-exciting dynamo process. Electrical currents flowing in the slowly moving molten iron generate the magnetic field. In addition to sources in Earth's core, the magnetic field observable at the planet's surface has sources in the crust and in the ionosphere and magnetosphere. The geomagnetic field varies on a range of scales, and a description of these variations is now made—ordered from low- to high-frequency variations—in both the space and time domains. The final section describes how Earth's magnetic field can be both a tool and a hazard to the modern world. First of all, however, methods of observing the magnetic field are described.

2. Geomagnetic Field Observations

2.1. Definitions

The geomagnetic field vector, **B**, is described by the orthogonal components X (northerly intensity), Y (easterly intensity), and Z (vertical intensity, positive downwards); total intensity F; horizontal intensity H; inclination (or dip) I (the angle between the horizontal plane and the field vector, measured positive downwards); and declination (or magnetic variation) D (the horizontal angle between true north and the field vector, measured positive eastwards). Declination, inclination, and total intensity can be computed from the orthogonal components using the following equations:

$$D = \arctan\frac{Y}{X} \qquad I = \arctan\frac{Z}{H} \qquad F = \sqrt{H^2 + Z^2}$$

where H is given by

$$H = \sqrt{X^2 + Y^2}\,.$$

The International System of Units (SI) unit of magnetic field intensity, strictly flux density, most commonly used in geomagnetism is the Tesla. At Earth's surface the total intensity varies from 24 000 nanotesla (nT) to 66 000 nT. Other units likely to be encountered are the Gauss (1 Gauss = 100 000 nT), the gamma (1 gamma = 1 nT), and the Ørsted (1 Ørsted = $(10^3/4\pi)$ A m^{-1}).

2.2. Observatories

A geomagnetic observatory is a location where absolute vector observations of Earth's magnetic field are recorded accurately and continuously, with a time resolution of one minute or less, over a long period. The site of the observatory must be magnetically clean and remain so for the foreseeable future. The earliest magnetic observatories where continuous vector observations were made began operation in the 1840s.

There are two main categories of instruments at an observatory. The first category comprises variometers that make continuous measurements of elements of the geomagnetic field vector, but in arbitrary units, for example millimeters of photographic paper in the case of photographic systems or electrical voltage in the case of fluxgates.

A fluxgate sensor comprises a core of easily saturable material with high permeability. Around the core there are two windings: an excitation coil and a pick-up coil. If an alternating current is fed into the excitation coil so that saturation occurs and if there is a component of the external magnetic field along the fluxgate element, the pick-up coil outputs a signal not only with the excitation frequency but also other harmonics related to the intensity of the external field component. Both analog and digital variometers require temperature-controlled environments and installation on extremely stable platforms (though some modern systems are suspended and therefore compensate for platform tilt). Even with these precautions they can still be subject to drift. They operate with minimal manual intervention and the resulting data are not absolute.

The second category comprises absolute instruments that can make measurements of the magnetic field in terms of absolute physical basic units or universal physical constants. The most common types of absolute instruments are the fluxgate theodolite for measuring *D* and *I* and the proton precession magnetometer for measuring *F*. In the former, the basic unit is an angle. The fluxgate sensor mounted on the telescope of a nonmagnetic theodolite is used to detect when it is perpendicular to the magnetic field vector. Collimation errors between the fluxgate sensor and the optical axis of the theodolite, and within the theodolite, are minimized by taking readings from four telescope positions. With the fluxgate sensor operating in null-field mode, the stability and sensitivity of the sensor and its electronics are maximized. True north is determined by reference to a fixed mark of known azimuth. This can be determined astronomically or by using a gyro attachment. In a proton precession magnetometer, the universal physical constant is the gyromagnetic ratio of the proton, and the basic unit is time (frequency). Measurements with a fluxgate theodolite can only be made manually, whereas a proton magnetometer can operate automatically.

Figure 1. Locations of currently operating geomagnetic observatories

The locations of currently operating magnetic observatories are shown in Figure 1. It can be seen that the spatial distribution of the observatories is rather uneven, with a concentration in Europe and a dearth elsewhere in the world, particularly in the ocean areas.

2.3. Satellites

Since the 1960s, Earth's magnetic field has been observed intermittently by satellites. The first satellites measured only the strength of the magnetic field, sometimes using only a nonabsolute instrument, but beginning in 1999 there have been a number of satellite missions attempting to measure the full field vector, using star cameras to establish the direction of a triaxial fluxgate sensor. An absolute intensity instrument is normally also carried, and both magnetic instruments are kept remote from the main body of the satellite by mounting them at the end of a nonmagnetic boom. Satellites provide an excellent global distribution of data, but generally only last for a short period (i.e., months to a few years).

Satellites which have provided valuable vector data for geomagnetic field modelling are Magsat, which flew in 1979 and 1980, and Orsted and CHAMP which were launched in 1999 and 2000 respectively and are still returning data in 2006. The Orsted satellite takes just over 2 years to sample all local times and flies in the altitude range 640-850 km. The CHAMP satellite samples all local times in 4-5 months and flies in the altitude range 350-450 km.

2.4. Other Direct Observations

Earth's magnetic field is observed in a number of other ways. These are repeat stations and surveys made on land, from aircraft and ships. Repeat stations are permanently marked sites where high-quality vector observations of Earth's magnetic field are made for a few hours, or sometimes a few days, every few years. Their main purpose is to track changes in the core-generated magnetic field.

Most aeromagnetic surveys are designed to map the crustal field. As a result, they are flown at altitudes lower than 300 m, and they cover small areas, generally once only, with very high spatial resolution. Because of the difficulty in making accurately oriented measurements of the magnetic field on a moving platform, these kinds of aeromagnetic surveys generally comprise total intensity data only. However, between 1953 and 1994 the Project MAGNET program collected high-level three-component aeromagnetic data specifically for modeling the core-generated field. The surveys were mainly over the ocean areas of Earth, at middle to low latitudes. A variety of platforms and instrumentation were used; the most recent set-up included a fluxgate vector magnetometer mounted on a rigid beam in the magnetically clean rear part of the aircraft, a ring laser gyro fixed at the other end of the beam, and a scalar magnetometer located in a stinger extending some distance behind the aircraft's tail section.

Modern marine magnetic surveys are also invariably designed to map the crustal field, but with careful processing it is possible to obtain information about the core-generated field from the data. In a marine magnetic survey, a scalar magnetometer is towed some distance behind a ship, usually along with other geophysical equipment, as it makes either a systematic survey of an area or traverses an ocean.

Prior to the establishment of observatories and an absolute method of measuring magnetic intensity by Gauss in the 1830s, magnetic observations were madeby mariners engaged in merchant and naval shipping, as well as by others. These measurements were mainly of declination and serve to extend the global historic data set back to the beginning of the seventeenth century.

2.5. Indirect Observations

Prior to the seventeenth century, indirect observations of Earth's magnetic field are possible from archaeological remains and rocks using paleomagnetic techniques. The subject of rock magnetism and paleomagnetism is covered elsewhere in this encyclopedia (see *Rock Magnetism and Paleomagnetism*).

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Bibliography

Campbell W.H. (1997). *Introduction to Geomagnetic Fields*, 290 pp. Cambridge, UK: Cambridge University Press. [This book is an introduction to geomagnetism suitable for those who are not familiar with the field, with an emphasis on external fields.]

Jankowski J. and Sucksdorff C. (1996). *IAGA Guide for Magnetic Measurements and Observatory Practice*, 235 pp. Boulder, CO: International Association of Geomagnetism and Aeronomy. [This book describes magnetic observatory instrumentation and procedures and is suitable for those setting up or running an observatory and using observatory data.]

Jacobs J.A. (1987). *Geomagnetism Volumes 1, 2, and 3*, 627, 579, and 533 pp., respectively. London: Academic Press. [Volume 1: history of geomagnetism, instrumentation, and overviews of main and crustal fields. Volume 2: origins of Earth's magnetic field and that of the moon and other planets. Volume 3: rock magnetism, paleomagnetism and the ancient magnetic field behavior, conductivity structure of Earth, indices of geomagnetic activity, and magnetic field characteristics during solar quiet conditions.]

Jacobs J.A. (1991). *Geomagnetism Volume 4*, 806 pp. London: Academic Press. [This volume covers the solar-terrestrial environment including the solar wind, the Earth's magnetosphere, magnetopause, magnetotail, ionosphere, pulsations, plasma waves, magnetospheric storms and substorms, and auroras.]

Merrill R.T., McElhinny M.W., and McFadden P.L. (1996). *The Magnetic Field of the Earth*, 531 pp. London: Academic Press. [This book is an introduction to geomagnetism suitable for those who are not familiar with the field, with an emphasis on internal fields and paleomagnetism.]

Parkinson W.D. (1983). *Introduction to Geomagnetism*, 433 pp. Edinburgh, UK: Scottish Academic Press. [This book is an introduction to geomagnetism suitable for those who are not familiar with the field.]

Biographical Sketch

Dr **Susan MacMillan** ,is a senior geophysicist at the British Geological Survey. She acquired her doctoral degree in 1989 and has since worked at the British Geological Survey (BGS) on a wide variety of projects concerning Earth's magnetic field. Her research interests include regional and global magnetic field modeling using satellite and ground-based data, as well as crustal field modeling using aeromagnetic data. She has also devoted much time to developing applications for the geomagnetic field in industry. She is cochair of the International Association of Geomagnetism and Aeronomy Working Group V-MOD on "Geomagnetic Field Modeling". She is the author or coauthor of over 50 scientific publications and reports.