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2.7.6 Geomagnetism

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At any location near the Earth's surface, the magnetic field may be expressed as the vector sum of the contributions from three main sources: the main field generated in the Earth's core, the crustal field from local rocks and a rapidly varying external field from currents flowing in the upper atmosphere and magnetosphere, which also induces currents in the sea and the ground.

The field generated in the Earth's core accounts for most of the field observed at the Earth's surface, and its strength and direction vary slowly with time. The strength varies from about 23000 nanoTeslas (nT) in South America to 67000 nT near Antarctica. It is generated by a convective dynamo operating in the Earth's fluid outer core, which surrounds the solid inner core. The convection is driven by both thermal and compositional buoyancy sources at the inner core boundary. These are produced as the Earth slowly cools and iron in the iron-rich fluid alloy solidifies onto the inner core giving off latent heat and the light constituent of the alloy. The buoyancy forces cause fluid to rise and the Coriolis force, due to the Earth's rotation, causes the fluid flows to be helical. It is thought that this fluid motion twists and shears magnetic field, generating new magnetic field to replace that which diffuses away. The field observed at the Earth's surface approximates that of a dipole, currently tilted at about 10° to the axis of rotation of the Earth. However there are appreciable spatial departures from this simple model and they are best characterized at the Earth's surface by a spherical harmonic series.

In contrast, the strength and direction of the crustal field may be regarded as essentially constant, only varying over geological timescales. Its strength is generally less than 200 nT but there are a few locations where much larger, highly localized, crustal fields exist. Aeromagnetic and marine magnetic surveys help map the geology as different rock types and formations have different magnetic signatures.

The strength of the external field depends on latitude and at high latitudes during magnetic storms it may vary by over 1000 nT on timescales of minutes to hours and can take any direction, leading to variations in the direction of the total field of a few degrees. These magnetic storms are caused by the interaction of the solar wind with the Earth's magnetic field. The solar wind is a stream of charged particles continuously emitted by the Sun and its pressure on the Earth's magnetic field creates a bounded comet-shaped region surrounding the Earth called the magnetosphere. When there is a disturbance in the Earth-directed solar wind, often caused by activity associated with sunspots such as coronal mass ejections and coronal holes, the current systems inside the magnetosphere are enhanced and cause magnetic disturbances and storms at the Earth's surface. In particular, the high latitude current systems are enhanced as charged particles of solar origin are accelerated down the magnetic field lines. These energetic charged particles collide with atoms and molecules in the upper atmosphere, resulting in often spectacular light displays at high latitudes, the aurorae.

The external field is also influenced by the direction of the Sun and this results in smaller and regular diurnal and seasonal variations. These variations are caused mainly by electrical currents in the upper atmosphere, peaking at altitudes around 110 km above the Earth's surface. The upper atmosphere is ionized by the Sun's ultraviolet and X-radiation to create the ionosphere, and the free ions and electrons are moved by winds and tides arising from the heating effects of the Sun and the gravitational pull of the Sun and the Moon. This creates the required conditions for a dynamo to operate, i.e. motion of a conductor in a magnetic field. Both the irregular and regular variations in the external field are affected by the approximately 11 year solar activity cycle.

In practice it is difficult to separate out these three main sources from observations of the geomagnetic field vector because of overlaps in the spatial and temporal frequency domains. However, if it is assumed that the region where observations are made is source-free, the magnetic field **B** is then the negative gradient of a scalar potential V which satisfies Laplace's equation $\nabla^2 V = 0$. The scalar potential is the sum of the potentials from internal sources, V_i, and external sources, V_e. A solution to Laplace's equation for V_i is

$$V_i(r,\theta,\lambda,t) = a\sum_{n=1}^{n_{i\max}}\left(\frac{a}{r}\right)^{n+1}\sum_{m=0}^{n}\Big(g_n^m(t)\cos(m\lambda) + h_n^m(t)\sin(m\lambda)\Big)\ \mathrm{P}_n^m(\theta)$$

where (r,θ,λ) are radius, colatitude and longitude of the point of interest, α is the Earth's reference radius, $(g_n^m(t), h_n^m(t))$ are the Gauss spherical harmonic coefficients of order m and degree n at time t, $n_{i\ max}$ is the maximum degree of the spherical harmonic expansion for the internal potential V_i, and P_n^m are the Schmidt semi-normalized Legendre polynomials of θ. **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). The orthogonal components can be computed from the potential using the equations:

$$X = -\frac{1}{r}\frac{\partial V}{\partial \theta}, \quad Y = -\frac{1}{r\cos\theta}\frac{\partial V}{\partial \lambda}, \quad Z = \frac{\partial V}{\partial r}$$

and *D*, *I*, *H* and *F* can be computed from the orthogonal components using the equations:

$$D = \tan^{-1}(Y/X), \quad I = \tan^{-1}(Z/H), \quad H = \sqrt{X^2+Y^2}, \quad F = \sqrt{H^2+Z^2}.$$

The Gauss coefficients constitute a spherical harmonic model of the Earth's magnetic field and one such model is the World Magnetic Model. This model is used to produce global charts of the magnetic field and its annual rate of change and these can be viewed at www.geomag.bgs.ac.uk. The coefficients of the current version are listed in the following table. Units are nT for the main-field coefficients $(g_n^m(t), h_n^m(t))$ at 2005.0, and nT/year for the secular-variation coefficients $(\dot{g}_n^m(t), \dot{h}_n^m(t))$ valid for 2005.0-2010.0.

n	m	g_n^m	h_n^m	$\dot{g}_n^m$	$\dot{h}_n^m$
1	0	-29556.8		8.0	
1	1	-1671.7	5079.8	10.6	-20.9
2	0	-2340.6		-15.1	
2	1	3046.9	-2594.7	-7.8	-23.2
2	2	1657.0	-516.7	-0.8	-14.6
3	0	1335.4		0.4	
3	1	-2305.1	-199.9	-2.6	5.0
3	2	1246.7	269.3	-1.2	-7.0
3	3	674.0	-524.2	-6.5	-0.6
4	0	919.8		-2.5	
4	1	798.1	281.5	2.8	2.2
4	2	211.3	-226.0	-7.0	1.6
4	3	-379.4	145.8	6.2	5.8
4	4	100.0	-304.7	-3.8	0.1
5	0	-227.4		-2.8	

n	m	g_n^m	h_n^m	$\dot{g}_n^m$	$\dot{h}_n^m$
9	0	5.6			
9	1	9.9	-20.1		
9	2	3.5	12.9		
9	3	-7.0	12.6		
9	4	5.1	-6.7		
9	5	-10.8	-8.1		
9	6	-1.3	8.0		
9	7	8.8	2.9		
9	8	-6.7	-7.9		
9	9	-9.1	6.0		
10	0	-2.3			
10	1	-6.3	2.4		
10	2	1.6	0.2		
10	3	-2.6	4.4		
10	4	0.0	4.8		

5	1	354.6	42.4	0.7	0.0
5	2	208.7	179.8	-3.2	1.7
5	3	-136.5	-123.0	-1.1	2.1
5	4	-168.3	-19.5	0.1	4.8
5	5	-14.1	103.6	-0.8	-1.1
6	0	73.2		-0.7	
6	1	69.7	-20.3	0.4	-0.6
6	2	76.7	54.7	-0.3	-1.9
6	3	-151.2	63.6	2.3	-0.4
6	4	-14.9	-63.4	-2.1	-0.5
6	5	14.6	-0.1	-0.6	-0.3
6	6	-86.3	50.4	1.4	0.7
7	0	80.1		0.2	
7	1	-74.5	-61.5	-0.1	0.6
7	2	-1.4	-22.4	-0.3	0.4
7	3	38.5	7.2	1.1	0.2
7	4	12.4	25.4	0.6	0.3
7	5	9.5	11.0	0.5	-0.8
7	6	5.7	-26.4	-0.4	-0.2
7	7	1.8	-5.1	0.6	0.1
8	0	24.9		0.1	
8	1	7.7	11.2	0.3	-0.2
8	2	-11.6	-21.0	-0.4	0.1
8	3	-6.9	9.6	0.3	0.3
8	4	-18.2	-19.8	-0.3	0.4
8	5	10.0	16.1	0.2	0.1
8	6	9.2	7.7	0.4	-0.2
8	7	-11.6	-12.9	-0.7	0.4

10	5	3.1	-6.5		
10	6	0.4	-1.1		
10	7	2.1	-3.4		
10	8	3.9	-0.8		
10	9	-0.1	-2.3		
10	10	-2.3	-7.9		
11	0	2.8			
11	1	-1.6	0.3		
11	2	-1.7	1.2		
11	3	1.7	-0.8		
11	4	-0.1	-2.5		
11	5	0.1	0.9		
11	6	-0.7	-0.6		
11	7	0.7	-2.7		
11	8	1.8	-0.9		
11	9	0.0	-1.3		
11	10	1.1	-2.0		
11	11	4.1	-1.2		
12	0	-2.4			
12	1	-0.4	-0.4		
12	2	0.2	0.3		
12	3	0.8	2.4		
12	4	-0.3	-2.6		
12	5	1.1	0.6		
12	6	-0.5	0.3		
12	7	0.4	0.0		
12	8	-0.3	0.0		
12	9	-0.3	0.3		

8	8	-5.2	-0.2	0.4	0.4

12	10	-0.1	-0.9		
12	11	-0.3	-0.4		
12	12	-0.1	0.8		

The input data for producing these global models are observations collected around the world at observatories (of which there are currently about 180), networks of repeat stations and latterly, measurements from satellites. The distribution of observatories is largely determined by the location of habitable land and by the availability of local expertise, funds, and energy supply, and as result, it is uneven and a little sparse in some regions. Some observatories have had to move because of encroaching urbanization. International scientific campaigns such as the first International Polar Year in 1882/3, the second International Polar Year in 1932/3 and the International Geophysical Year in 1957/8 encouraged the opening of many observatories around the world. Geomagnetism is a cross-disciplinary science, and as a result, observatories are run by a wide variety of institutes whose interests range from geology, mapping, geophysics (including seismology and earthquake prediction), meteorology to solar-terrestrial physics and astronomy. Most observatories now run three sets of equipment: triaxial fluxgate systems making automatic non-absolute vector measurements, proton precession magnetometers making automatic absolute scalar measurements and fluxgate theodolites requiring manual operation to make absolute vector observations.

From the late 1950s to the 1970s a series of Russian and American satellites made magnetic field observations but it was not till 1979 that the first satellite made precise, oriented observations of the field. Magsat, an American mission, collected vector data for 7 months at altitudes up to 550 km. It was another 20 years till the next vector satellite surveys. The Danish-led mission Ørsted was launched in 1999 into a higher orbit than Magsat and lasted over 6 years. The German-led mission CHAMP was launched in 2000 into a lower orbit thsn Magsat and is expected to return data till 2008. Triaxial fluxgate and absolute total intensity magnetometers are placed on a boom to keep them remote from the magnetic effects of the main body of the satellite and accurate sensor orientation is achieved by star cameras. These satellites provide excellent global coverage of homogeneous data and it is expected that these surveys will be augmented with other satellite datasets such as those from the European satellite constellation, Swarm, due to be launched in 2009.

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