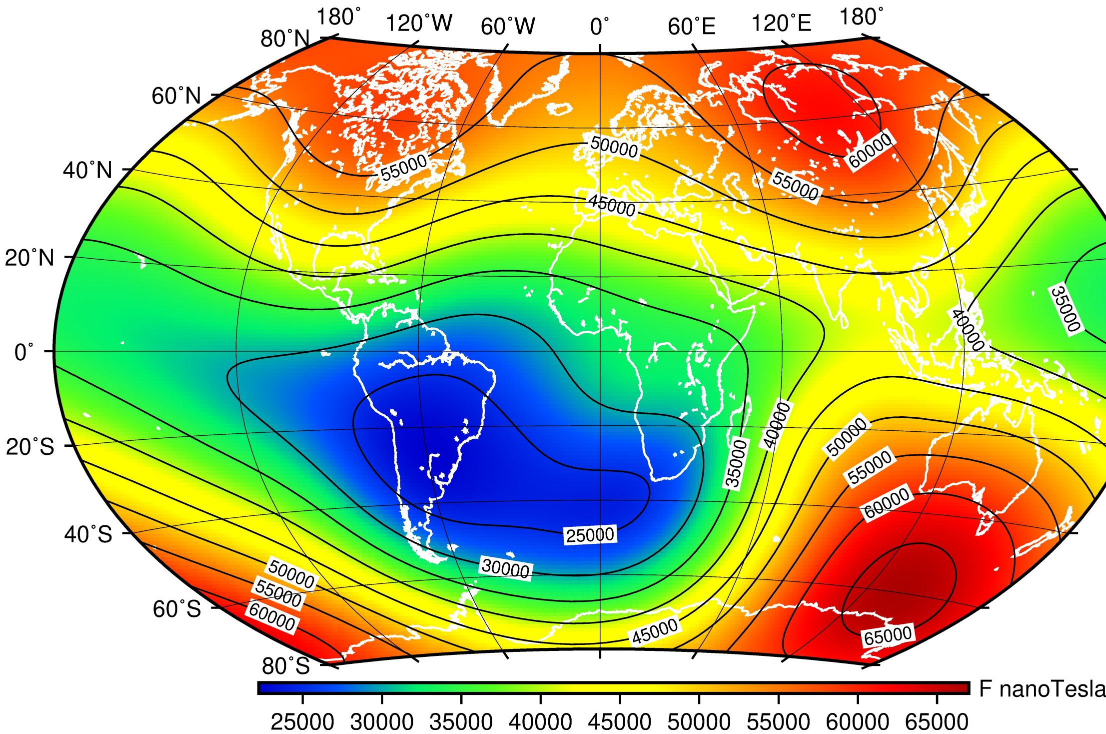
Chapter 7

Earth's Magnetic Field



(British Geological Survey)

7 Earth's Magnetic Field

Earth's magnetic field shields the Earth from solar winds (Figure 1). Without a strong magnetic field solar winds would strip Earth of its atmosphere and evaporate our oceans, lakes and rivers leaving Earth a lifeless barren desert much like present day Mars. Earth's magnetic field is extremely important!

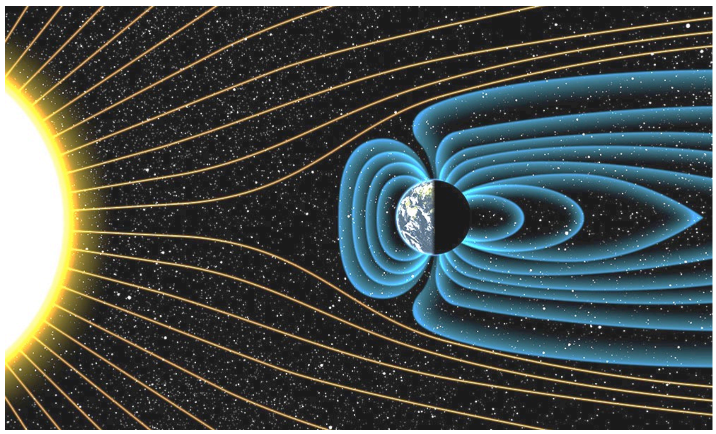


Figure 1 Earth's protective magnetic field (blue) diverts solar winds (yellow) around Earth (source: University of Rochester)

Earth's magnetic field is generally referred to as the geomagnetic field.

Over 93% of the geomagnetic field is generated by convection currents deep within the Earth. These currents produce the core or main magnetic field. The remainder of the geomagnetic field is produced by electrical currents circulating in the ionosphere at altitudes between 90 to 1000 km, and electrical currents in the magnetosphere. The magnetospheric electrical currents are at an altitude of several Earth radii (Earth's radius is 6,371 km). A small segment of the magnetic field (only a few percent) is formed by magnetized material in Earth's crust. These secondary sources add to or subtract from the core field causing the total magnetic field to vary in time, location on Earth, and with altitude above the Earth.

7.1 Core Magnetic Field

The structure of the Earth and its internal temperature profile are shown in Figure 2 and Figure 3 respectively. The Earth's curst ranges from 5 – 70 km in depth. Below the curst Earth's mantle extends to a depth of 2,890 km, making it the thickest part of the Earth. The mantle consists of silicate rocks rich in iron and magnesium. The outer core is composed of nickel-iron so hot that it is in a molten state. The high temperature ionizes some of the nickel-iron atoms creating an electrically charged plasma. Temperatures in the Earth's inner core are even higher. However, instead of being liquid as one would expect, the inner core is compressed into solid nickel-iron by the Earth's gravity.

Thermal convection currents within the outer core transport hot molten nickel-iron from just above the inner core to the mantle as shown in Figure 4. The molten nickel-iron cools as it rises toward the mantle, becomes more dense, and gradually sinks back toward the inner core. As it sinks it is heated by the intense thermal radiation from the inner core. The molten nickel-iron expands, becomes buoyant, and again drifts outward toward the mantle beginning a new convection cycle.

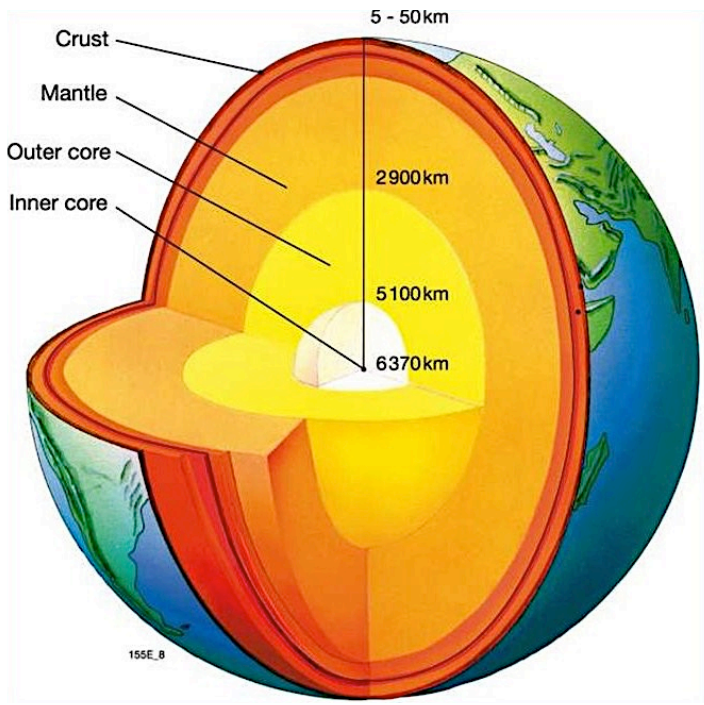


Figure 2 The Earth's Interior Structure (source: Lakshya Geography)

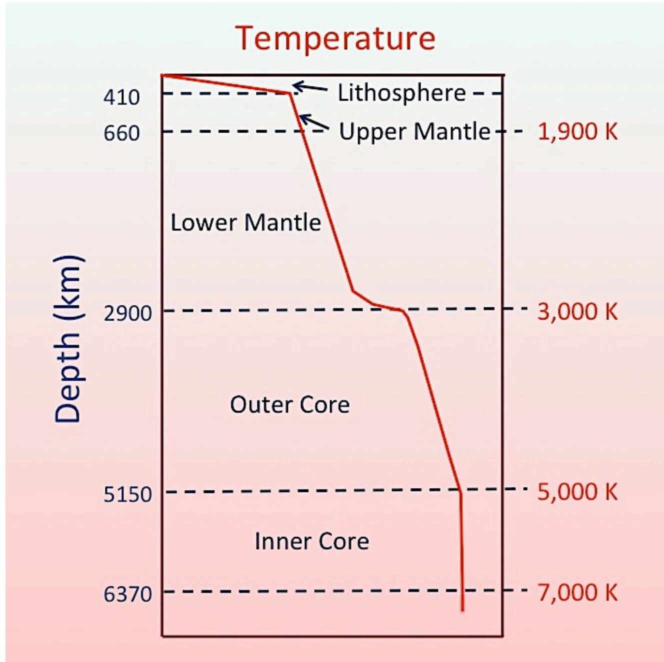


Figure 3 Temperature Profile of Earth's Interior (source: Wikipedia)

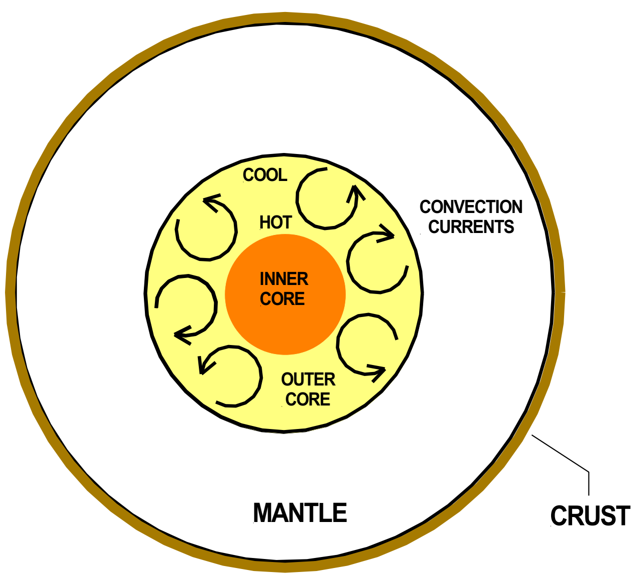


Figure 4 Outer Core Convection Currents (source: author)

Since the hot molten nickel-iron is a plasma, with an abundance of positively charged ions and negative electrons, the convective flow of this plasma creates circulating electrical currents within the outer core.

The electrical currents create a magnetic field in accordance with Ampere's Circulation Law. In this case, the Earth's magnetic field illustrated in Figure 5.

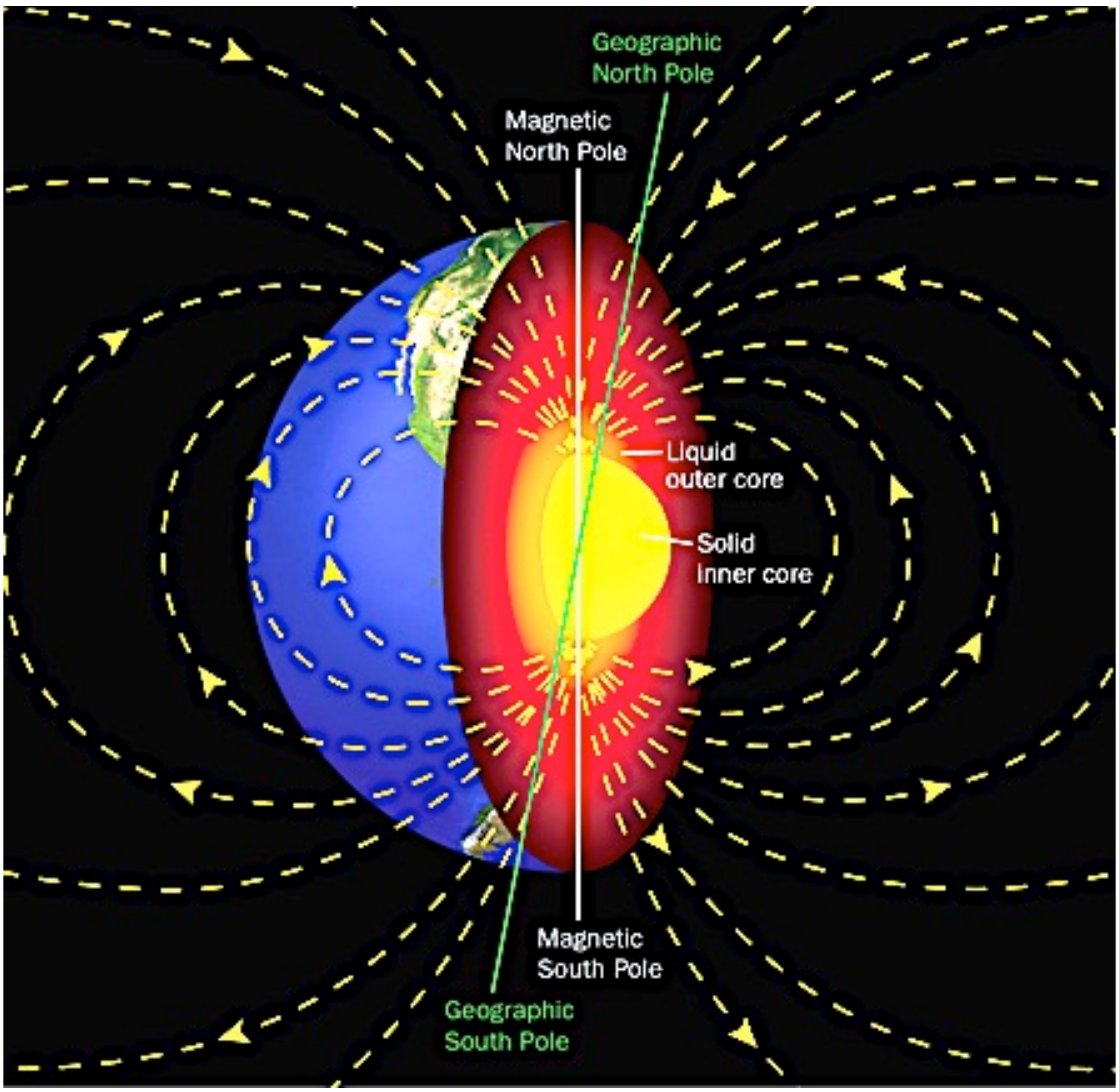


Figure 5 Earth's Magnetic Field (source: Quora)

7.2 Dipolar Field

To a good approximation, the geomagnetic field, illustrated in Figure 6, is a dipolar field. This field is similar to what would be produced if a large bar magnetic were positioned at the center of the Earth. Note in Figure 6 that the north magnetic pole (magnetic field lines flowing away from the Earth) is actually located in the south geographic polar region (in the Antarctic). In turn, the magnetic south pole (magnetic field lines flowing into the Earth) is located in the north geographic polar region, facts that are generally ignored.

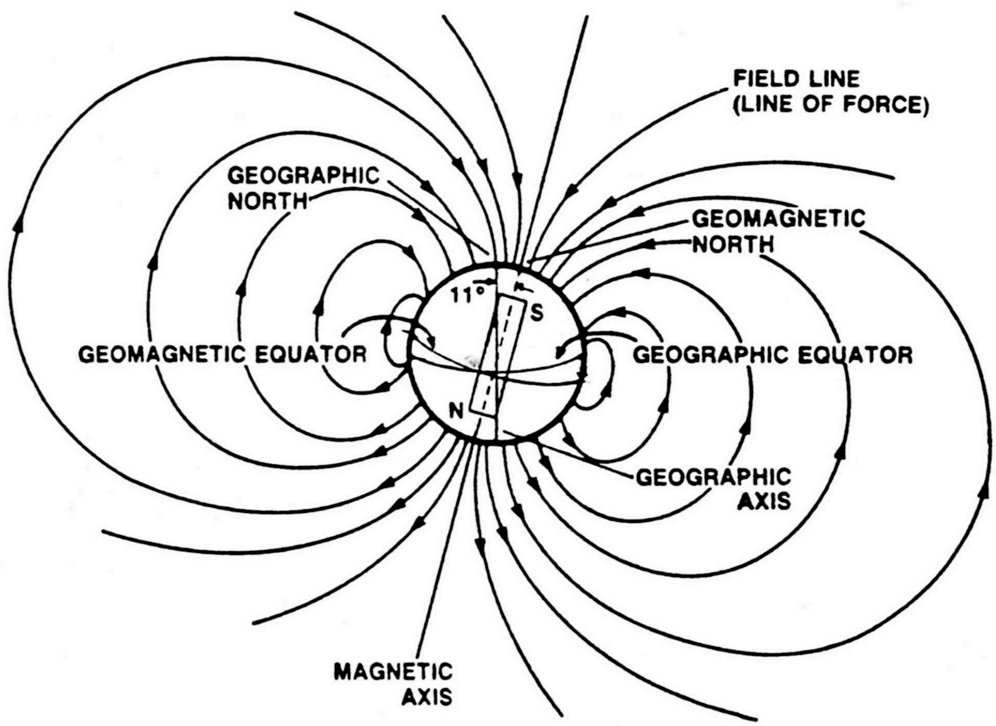


Figure 6 Simple model of Earth's magnetic field (source: McNamara)

The dipole axis of the geomagnetic field is not aligned with Earth's axis. Instead, it is off-set in the neighborhood of 500 km from the center of the Earth and titled at an angle of 11.5° relative to Earth's rotational axis as illustrated in Figure 7. Consequently, the geomagnetic equator, latitudes, longitudes, and meridians are also all titled by the same amount. All of the meridians, by definition, pass through the north and south geomagnetic poles. The prime geomagnetic meridian is defined as the meridian that also passes through the south geographic pole.

The geographic coordinate system is shown in Figure 8. The north and south geographic poles are at latitudes +90° and -90° respectively with the geographic equator at 0° latitude. The geographic prime meridian (0° longitude) passes through the geographic north and south poles and Greenwich England. East (positive) longitude is measured from the prime meridian eastward along the equator as shown in Figure 8. West (negative) longitude is measured from the prime meridian westward along the equator.

The north geomagnetic pole is geographically located at 78.5°N, 291°E (-111°W in the vicinity of northwestern Greenland) and the South pole is located at 78.5°S, 111°E. Note that the geographic north pole is at latitude 90° . Subtracting the title angle of 11.5° gives the geographical location of the geomagnetic poles, i.e.. 90° - 11.5° = 78.5° . However, there is considerable wobble in the geomagnetic field and the location of its poles.

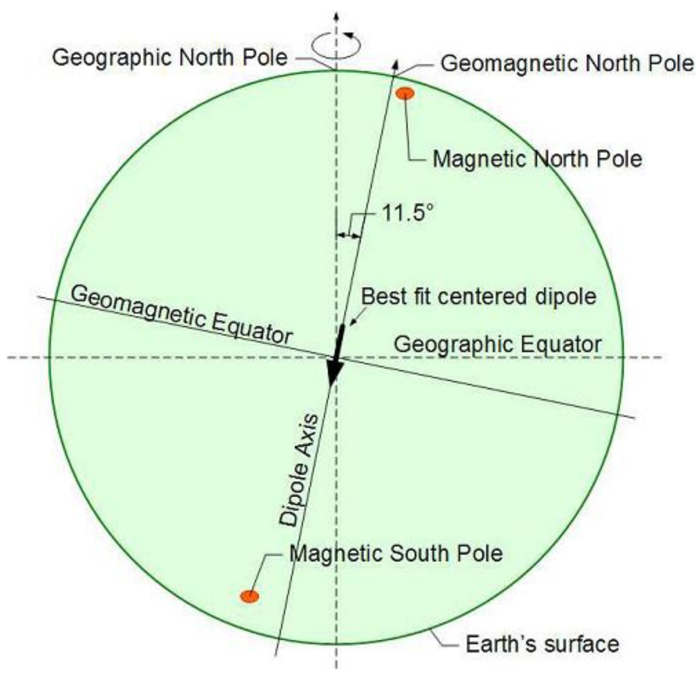


Figure 7 Tilt of magnetic dipole axis (source: Whitham D Reeve)

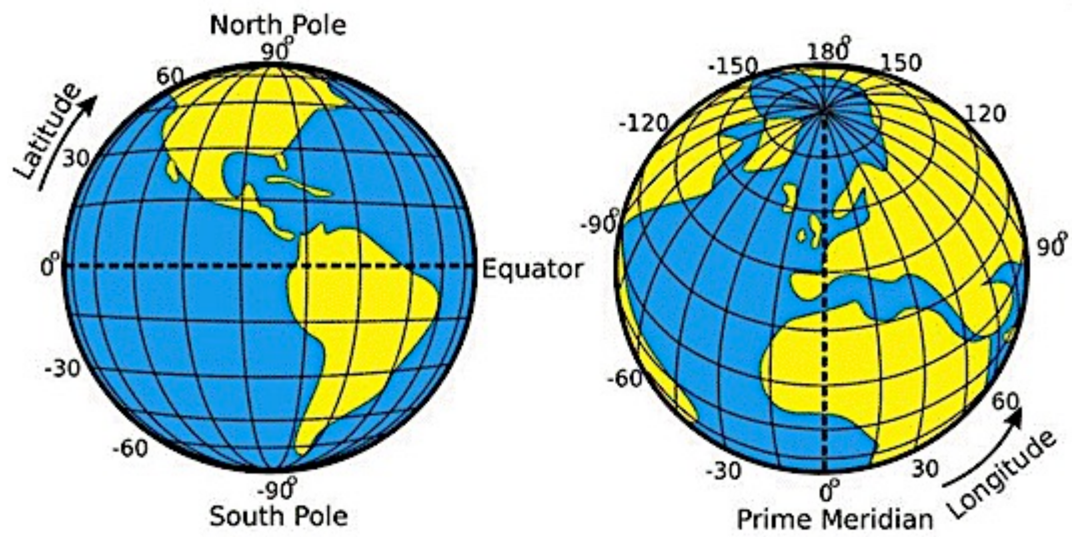
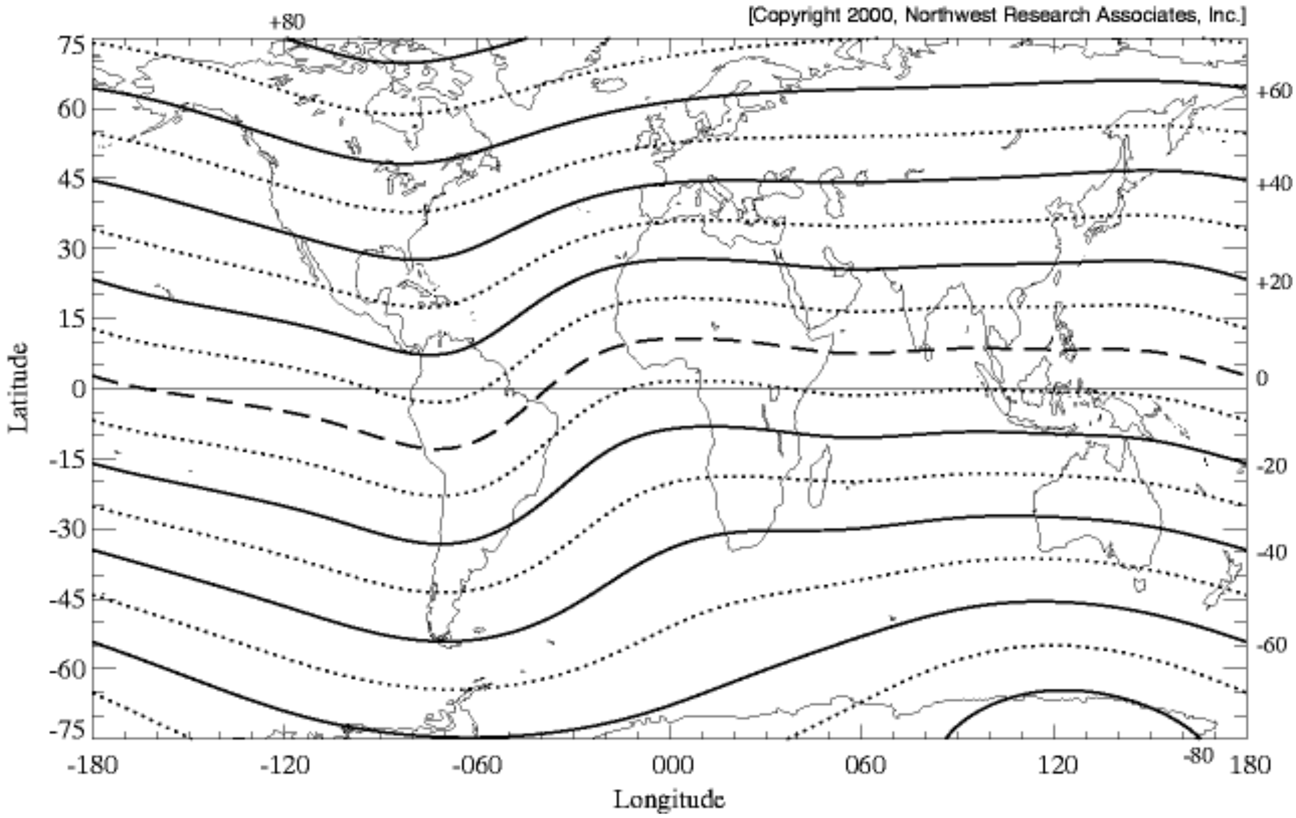


Figure 8 Geographic coordinates (source: Smithsonian Magazine)

Geomagnetic latitude contour lines are shown in Figures 9. The vertical scale on the right side of the chart is geomagnetic latitudes while geographic latitudes are provided by the scale on the left. The dashed line is the geomagnetic equator. The thin horizontal line at 0º latitude (left hand scale) is the geographical equator. Note that the geomagnetic latitude lines are shifted downward toward Antarctic in North and South America relative to Europe and Asia.



Geographic Latitude Scale Geomagnetic Latitude Scale

Figure 9 Geomagnetic Latitudes (source: Northwest Research Association)

7.3 Dip Angle

An important feature of the geomagnetic field is the magnetic field's dip angle. The geomagnetic field is horizontal (parallel to Earth's surface) only along the dip equator. At all other locations a compass needle free to move in all directions will point downward, as illustrated in Figure 10, instead of being horizontal. The same compass needle at the dip poles will be vertical (standing on end). Actual compass needles are constrained so that they only rotate horizontally.

The dip equator (where the dip angle is zero) does not coincide with the geomagnetic equator because the secondary sources of the magnetic field (ionospheric and magnetospheric electrical currents plus small amounts of crustal magnetism) distort the core field from its dipolar shape. This is an important point. The positions of the geomagnetic equator and poles assume that the geomagnetic field is perfectly dipolar. The dip equator and poles reflect the reality that, at Earth's surface, the geomagnetic field is not perfectly dipolar. It is distorted. It is interesting to note, however, that the field does become increasingly dipolar in shape as one gets further from Earth's surface.

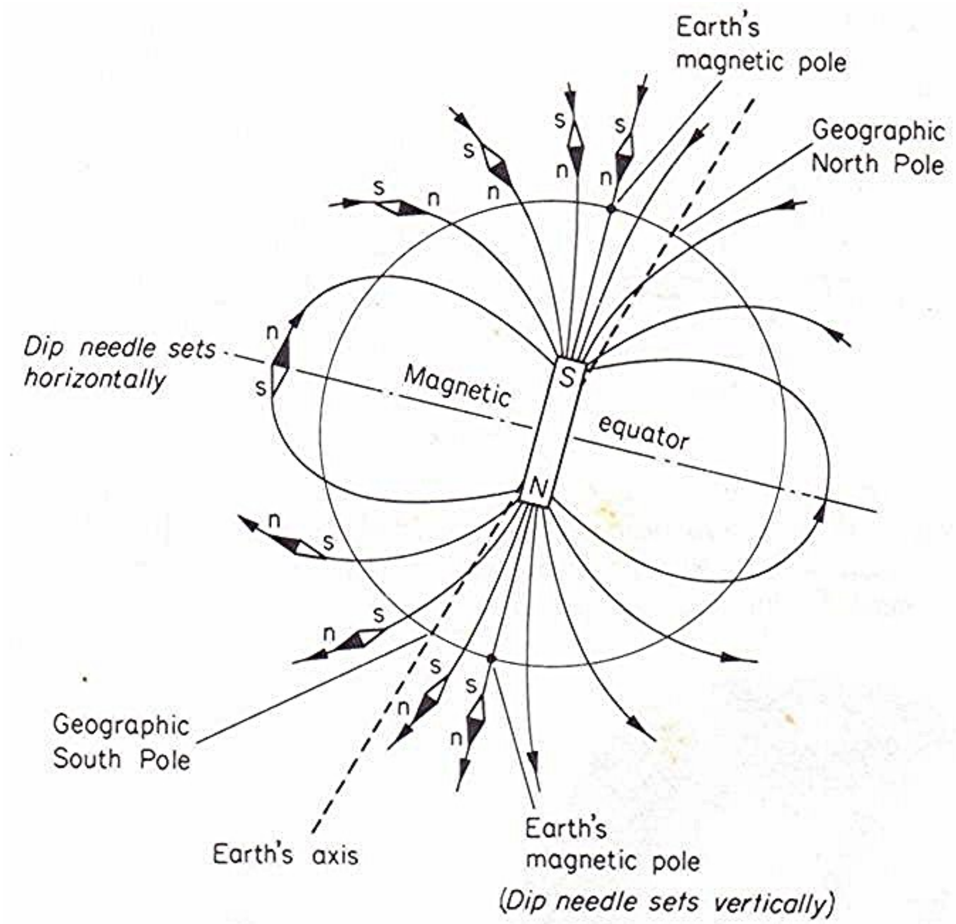


Figure 10 Geomagnetic Dip Angle (source: PhysicsMax.com)

The magnetic field lines are nearly vertical in the polar regions with dip angles approaching 90^o. The dip poles are the two locations, north and south, where the dip angles are exactly 90^o . The north dip pole is at 77.6^{o}N, 256.7^{o}E (over northern Canada), while the south dip pole is at 65.0^{o}S, 139.3^{o}E. The locations of the dip poles are different than the geomagnetic poles because again the Earth's actual magnetic field is more complex than the simple dipole field that we normally assume. The two red dots in Figure 7 represent the locations of the north and south dip poles. Notice in this figure that the position of the magnetic (dip) north pole is different from the geomagnetic north pole, and both are different from the geographic north pole.

Global magnetic dip angle contour lines are shown in Figure 11. For example, the dip angle over Florida, in the United States, is 60 degrees. That is, a compass needle free to move in all directions will be pointed downward over Florida, 60^o below horizontal.

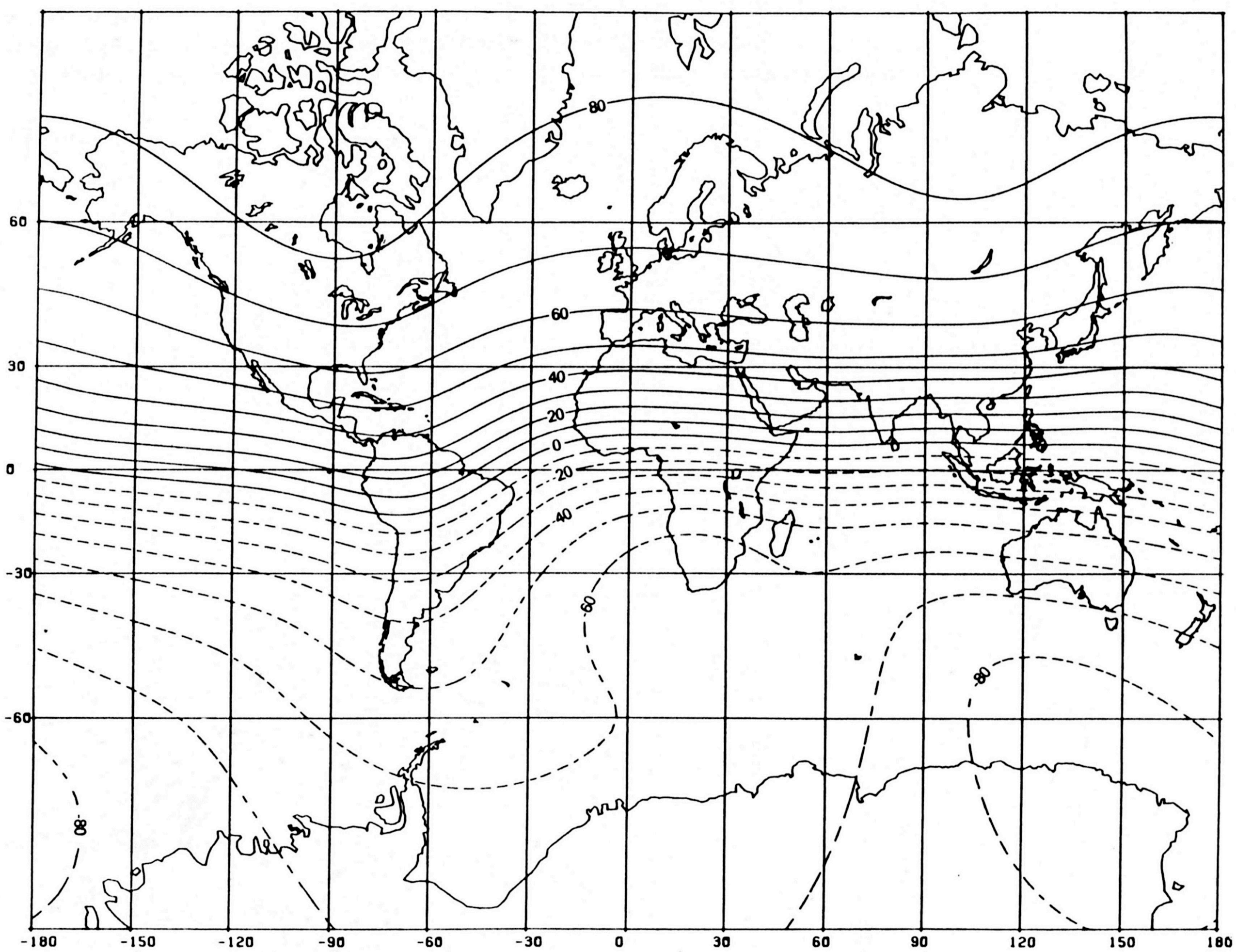


Figure 11 Magnetic Dip Angles (Source: Davies)

The geomagnetic and dip poles are not stationary. The geomagnetic north pole has moved at an average speed of about 1 km/year from 1900 to 1940. Since then it has accelerated moving at a rate of 7 km/year in 2015. The movement of the geomagnetic north pole is shown in the lower left corner of Figure 12. The magnetic (dip) pole is moving much faster migrating from northern Canada toward Siberia as shown in the middle of Figure 12. It has been moving about 10 to 20 km/year. Since 1980 the northern dip pole has accelerated reaching 55 km/year in 2005. It was closest to the geographic pole in 2020 and then continued its journey toward Siberia after that.

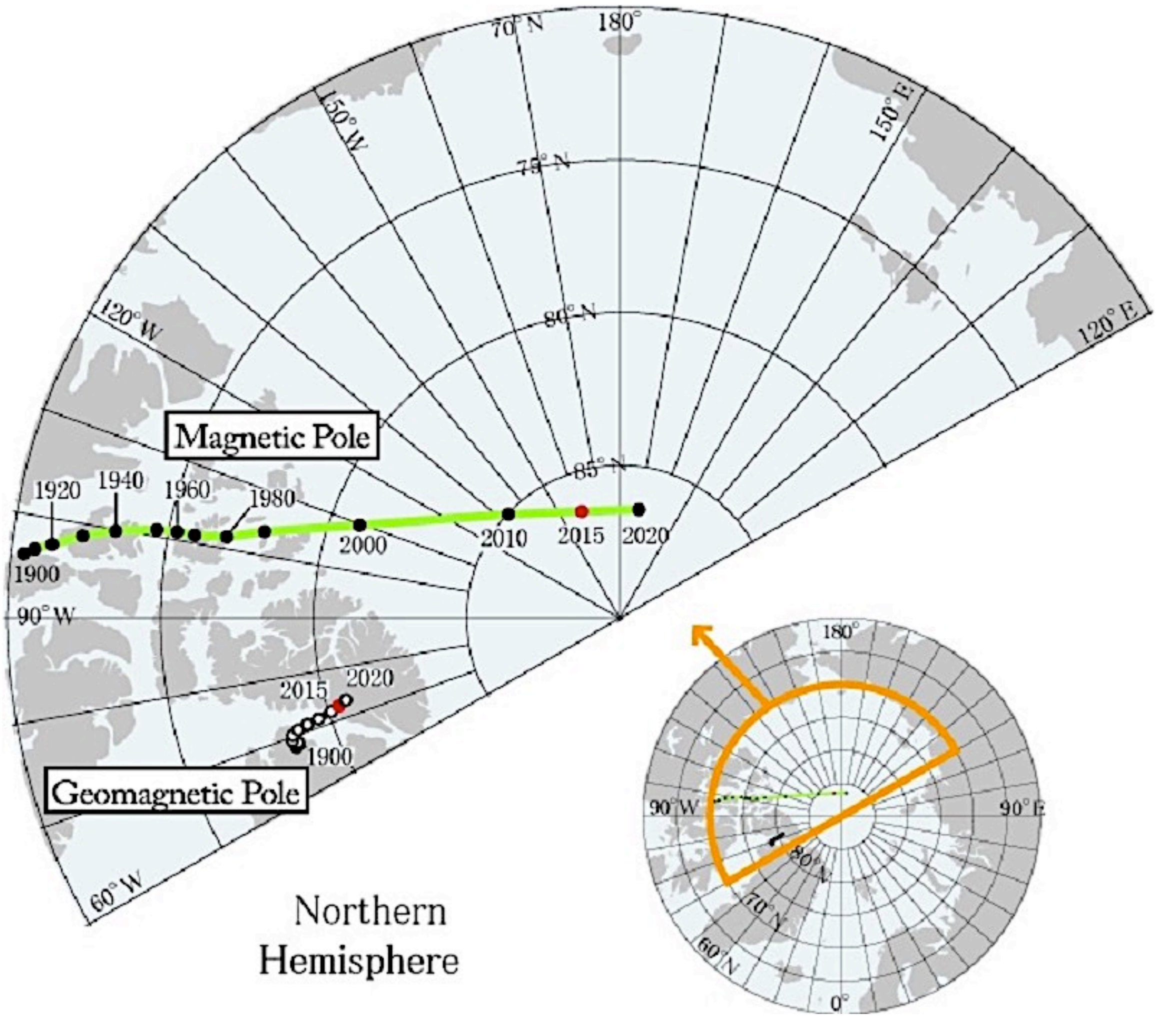


Figure 12 Movement of north magnetic from 1900 to 2020 (source: WBRZ)

7.4 Strength of Geomagnetic Field

The Earth's magnetic field is continuously monitored by approximately 150 geomagnetic observatories around the world. The majority of the observatories are located on the continents in the Northern Hemisphere as illustrated in Figure 13

The strength of the geomagnetic field, illustrated in Figure 14, varies at Earth's surface from about 25,000 nT in the south Atlantic to around 65,000 nT near the poles. Consequently, the magnetic field is twice as strong at the poles as it is in South America. 1 nT = 10^{-9} T. One tesla (T) = 10,000 gauss.

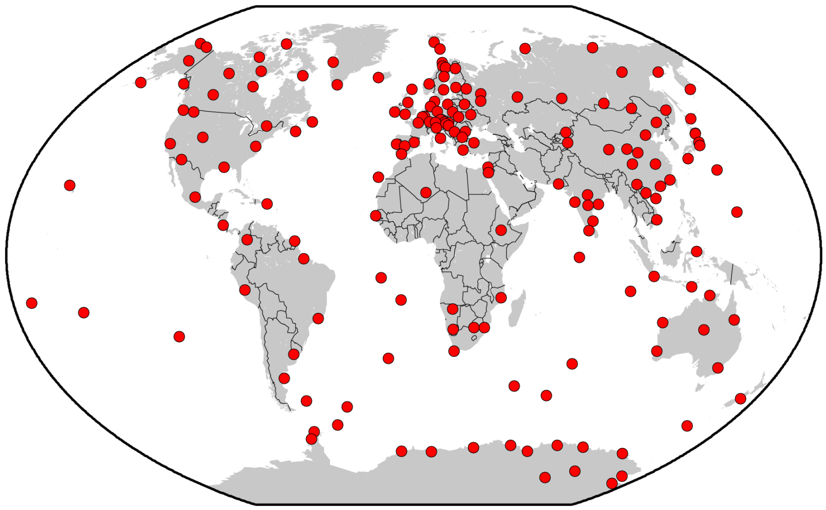


Figure 13 Locations of Geomagnetic Observatories (source: British Geological Survey)

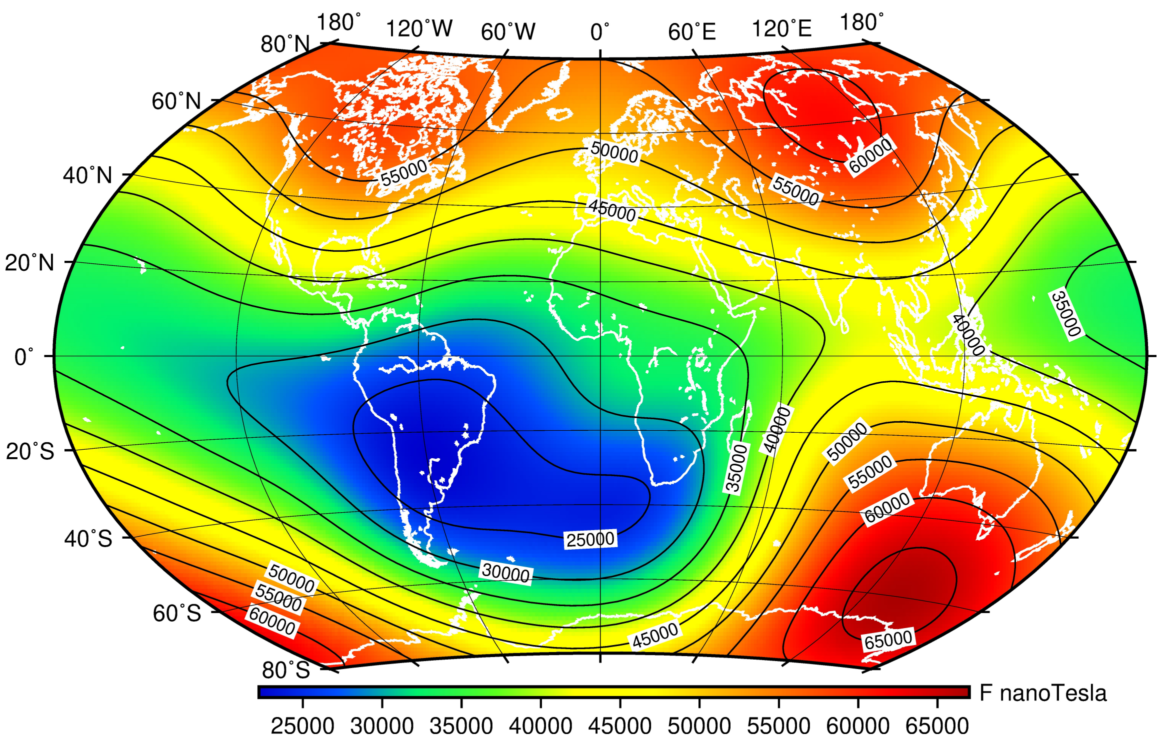


Figure 14 Global variations in magnetic field intensity   (source: British Geological Survey)

The strength of the core magnetic field has weakened by 7% on a global scale over the last 100 years. In certain regions, such as the south Atlantic, the strength of the core field has decreased even more. For instance, in 1900 the lowest field intensity on Earth was 25,460 nT close to the east coast of Brazil. By 1940 the field intensity had dropped to 24,590 nT and was 22,400 nT in 2015. In addition, this region of weak magnetic intensity has been moving westward at roughly 20 km/year. Further weakening of the magnetic field in this region is becoming a space weather concern since the Earth's magnetic field acts as a shield against the solar winds and high energy particles from the Sun and outer space. A continued decrease in the equatorial strength of the geomagnetic field poses a threat to spacecraft and increases radiation exposure to humans in space.

7.5 Magnetic Field Vector Components

Figure 15 illustrates the vector components of the geomagnetic field. The coordinate system (X, Y, and Z) is the geographic coordinates at some point of interest on Earth's surface. The X axis points to the geographic north pole. The Y axis points in the geographic east direction. Finally, the Z axis is the radial direction to the center of the Earth. The magnetic field B shown in Figure 15 has X, Y, and Z geographic components. H is the horizontal component of the field in the XY plane. H points to the geomagnetic north pole. The declination angle (D) is the angle between geographic north ("true North") and magnetic north (north as shown on a simple compass). I is the inclination, or dip angle, of the magnetic field vector below the horizontal XY plane.

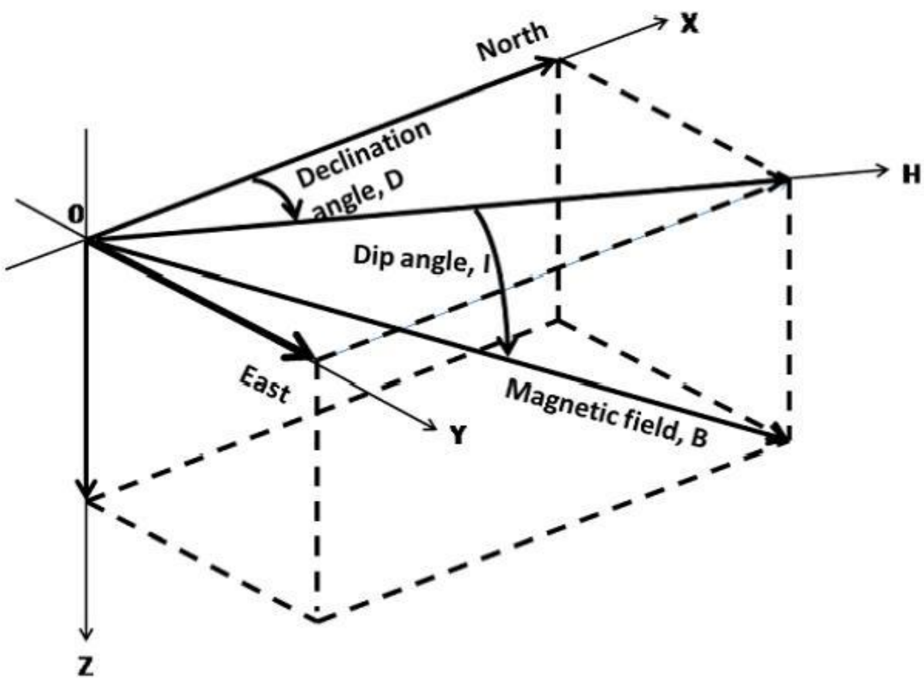


Figure 15 Magnetic field vector components (source: ResearchGate)

7.6 Magnetic Declination Calculator

It is often important to know the declination angle between magnetic north, as shown on a compass, and true north shown on a geographic map. An obvious situation is navigation whether hiking on foot or traveling by vehicle (car, boat, aircraft, etc.). In terms of skywave radio propagation it is important to know the geographic direct that a radio signal is propagating in when it leaves the transmitting antenna. To do this, the direction of propagation from the antenna is first determined using a simple compass. The magnetic bearing is then converted to the geographic bearing by knowing the location of the antenna (latitude and longitude) and the declination at that location.

Declination can be determined by going to the website www.skywave-radio.org clicking on the Tools tab, and then the Declination Calcu tab. The calculator retrieved is provided by NOAA (National Oceanic and Atmospheric Administration). Site registration is required to use the calculator but registration is easy consisting primarily of providing your email address. To register simply click on the “Registration” button on the upper right side of the web page. Once you have registered, enter your mailing address in the “Lookkup Latitude / Longitude” location box. Next click on the “Get & Add Lat / Lon” button. The required information is then automatically filled into the “Calculate Declination” box. Finally click on the “Calculate” button in the lower left corner of the web page. Your Declination information will appear. For example, for my mailing address in Thousand Oaks, CA (near Los Angles) the calculator returned a declination of 11° 48’ East. In my case magnetic north is east of true north so the true geographic bearing at my location is arrived at by adding the declination angle to the bearing given by a compass. If the direction of radio signal propagation from an antenna in Thousand Oaks is given as 100° magnetic (using a compass) then the geographic direction of propagation is

$$\text{Magnetic} + \text{declination} = 100^{\circ} + 11^{\circ}\ 48' = 111^{\circ}\ 48'\ \text{geographic}.$$

If the declination provided by the calculator is west, then the declination angle is subtracted from the magnetic bearing give by a compass.

7.7 Importance of the Geomagnetic Coordinate System

It is the Earth’s geomagnetic field, represented by the geomagnetic coordinate system (geomagnetic latitudes and longitudes), that determines the global variations in the ionosphere. Consequently, the geomagnetic coordinate system is far more important in describing and understanding the ionosphere, long distance radio communications, etc., than the more familiar geographic coordinate system. For example, at geographic mid-latitudes the ionosphere in the northern hemisphere can be significantly different than the ionosphere at a geographically equivalent point in the southern hemisphere because the geomagnetic field is different at the two locations.

References

Khazanov, George V.; “Space Weather Fundamentals”; CRC Press, 2016

Foukal, Peter; “Solar Astrophysics third edition”; Whiley-VCH Publishing Company, 2013

Hunsucker R. D.; Hargreaves, J. K.; “The High-Latitude Ionosphere and its Effects on Radio Prdopagation”; Cambridge University Press 2003

Davies, Kenneth; “Ionospheric Radio”; Peter Peregrinus Ltd.,1990

McNamara, Leo F.; “The Ionosphere: Communications, Surveillance, and Direction Finding”; Krieger Publishing Company, 1991

Carroll, Bradley W. and Ostlie, Dale A.; “An Introduction to Modern Astrophysics”; Addison-Wesley Publishing Company Inc., 1996

Goodman, John M.; “Space Weather & Telecommunications”; Springer Science+Business Media Inc. 2005

Cander, Ljiljana R.; “Ionospheric Space Weather”; Springer Nature Switzerland AG 2019

Moldwin, Mark; “An Introduction to Space Weather”; Cambridge University Press, 2008

Campbell, Wallace H.; “Introduction to Geomagnetic Fields”; Cambridge University Press, 2003

Golub, Leon and Pasachoff, Jay M.; “Nearest Star The Surprising Science of Our Sun second edition”; Cambridge University Press, 2014

Levis, Curt A. ; Johnson, Joel T.; and Teixeira, Fernando L.; “Radiowave Propagation Physics and Applications”; John Wiley & Sons, Inc., 2010

Nichols, Eric P.; “Propagation and Radio Science”; The American Radio Relay League, Inc. 2015

Yeang, Chen-Pang; “Probing The Sky With Radio Waves”; The University of Chicago Press, 2013

Devoldere, John; “Low-Band DXing” fourth edition; ARRL, 2005

Loff, Sarah: ”Explorer and Early Satellites”; National Aeronautics and Space Administration, Aug 3, 2017

Minzner, R. A.; “The 1976 Standard Atmosphere Above 86 km Altitude” NASA Goddard Space Flight Center, 1976

Ahrens, C. Donald; “Essentials of Meteorology”; Wadsworth Publishing Company, 1998