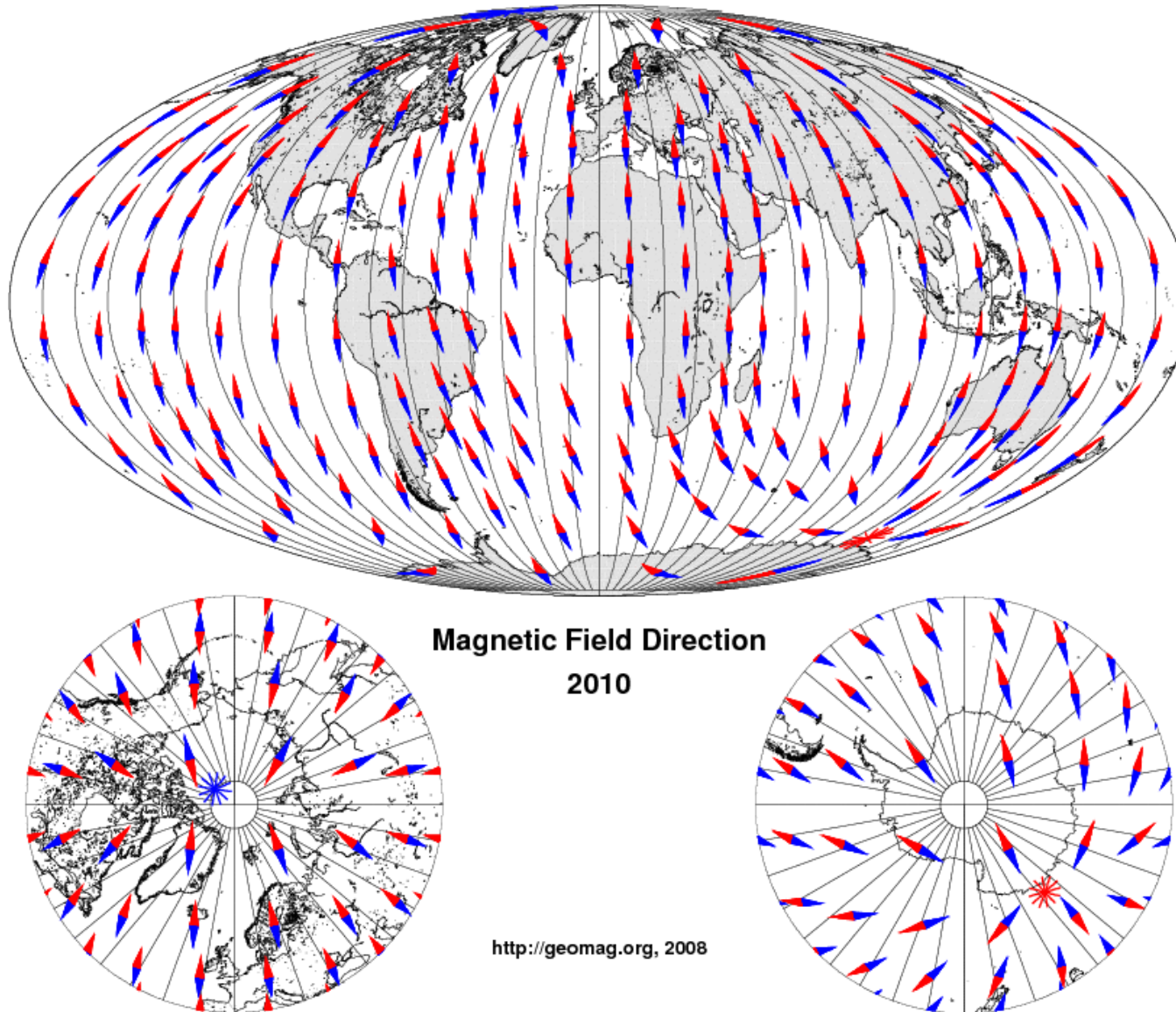


Chapter 2

Basic definitions of geomagnetism

Content

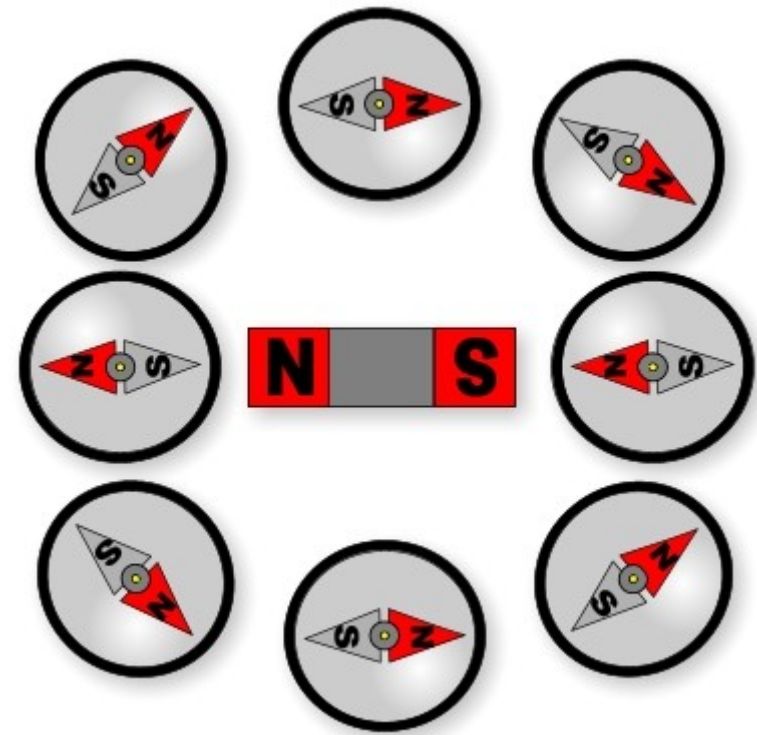
- The Earth has a magnetic field
- The Earth's magnetic field as vectors in geographic coordinates
- Sources of the Earth's magnetic field



Orientation of compass needles distributed over the surface of the Earth. True North is indicated by the direction of the black lines. The angle between the pointing direction of a compass needle and True North is called magnetic declination.

The Earth has a magnetic field

- On the Earth's surface, a small, freely turning magnetic needle (e.g., a compass needle) aligns itself roughly with the north-south direction.
- The head of the needle pointing northward is called the north pole (N) of the needle, and the head pointing southward is called the south pole (S).
- If a magnetic needle at a certain location aligns itself with a certain direction, it is said that there is a magnetic field at that location.
- According to observations, the Earth is surrounded by a magnetic field that varies with time and location.



Magnetic field

- The tesla (symbol T) is the SI derived unit of magnetic flux density (symbol B), also called the magnetic field.

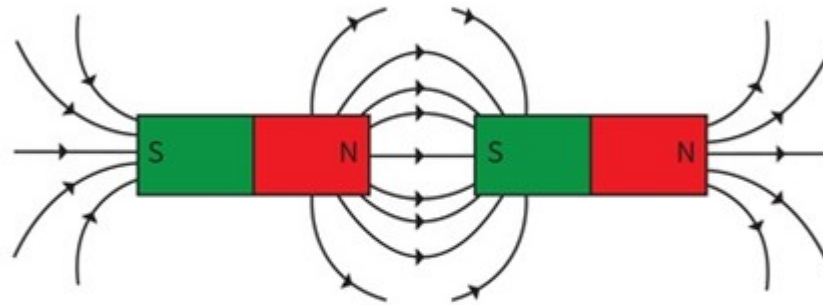
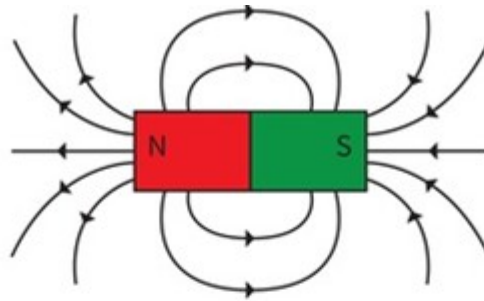
$$T = \frac{\text{kg}}{\text{A} \cdot \text{s}} = \frac{\text{N}}{\text{A} \cdot \text{m}}$$

- The magnetic field at any given point is specified by both a direction and a magnitude (or strength); it is a vector field. We will use the notations:

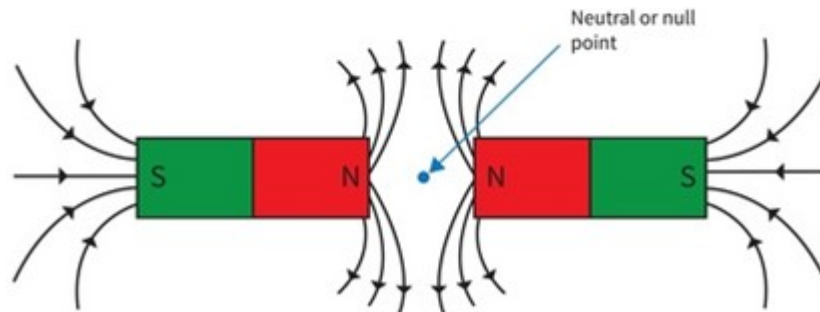
Magnetic field vector: \mathbf{B}

Magnetic field strength: $B = |\mathbf{B}|$

- The direction of the magnetic field is defined as the direction toward which the N-pole of a freely turning magnetic needle points when the needle is in the field.
- The magnetic field is represented by magnetic field lines, which show the direction of the field at different points.



Attraction between opposite poles



Repulsion between like poles

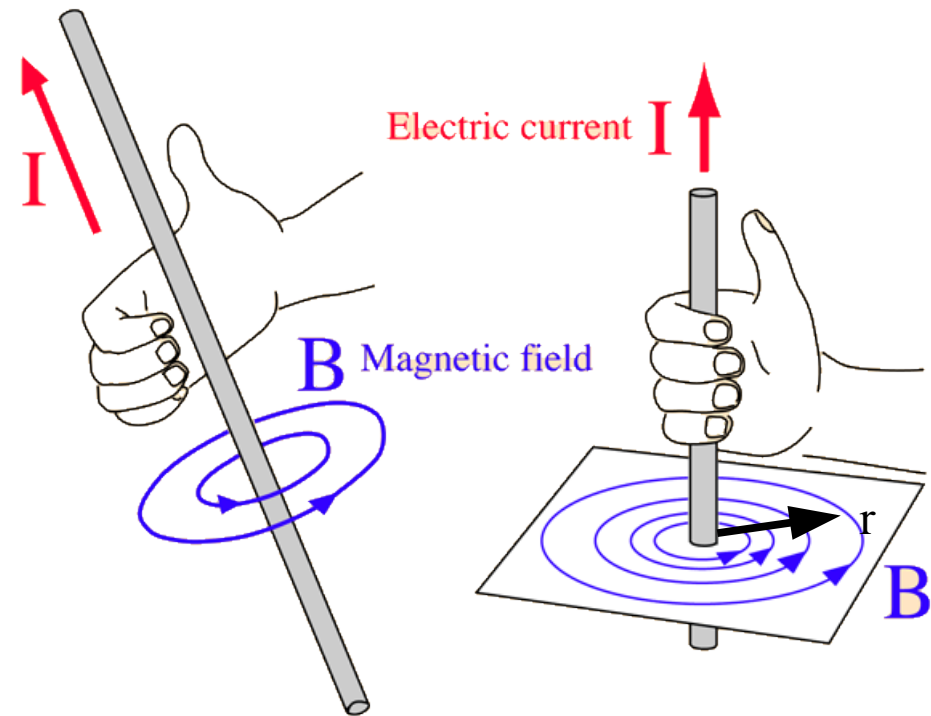
Electric current I [A] in an infinitely long, straight wire generates a magnetic field B [T] around the wire:

- The direction of the field can be deduced using the right hand rule (Figure).
- The amplitude at the distance r [m] is given by Ampère's law:

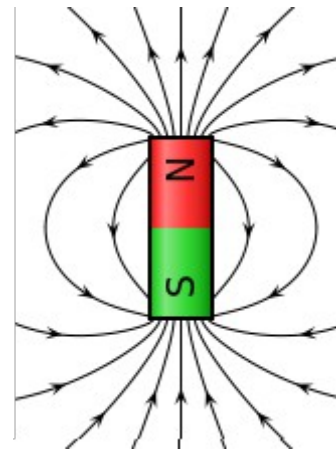
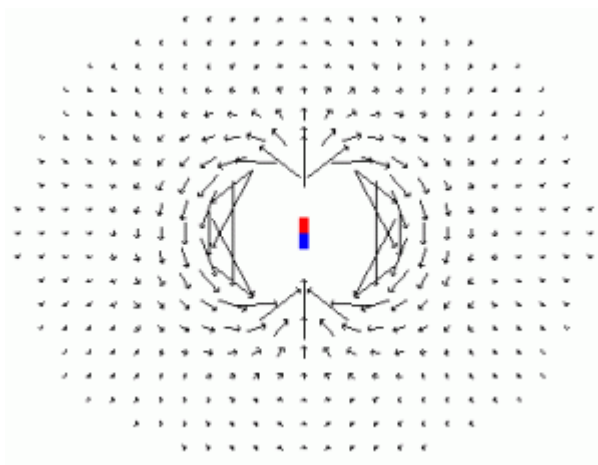
$$B = \frac{\mu_0 I}{2\pi r}$$

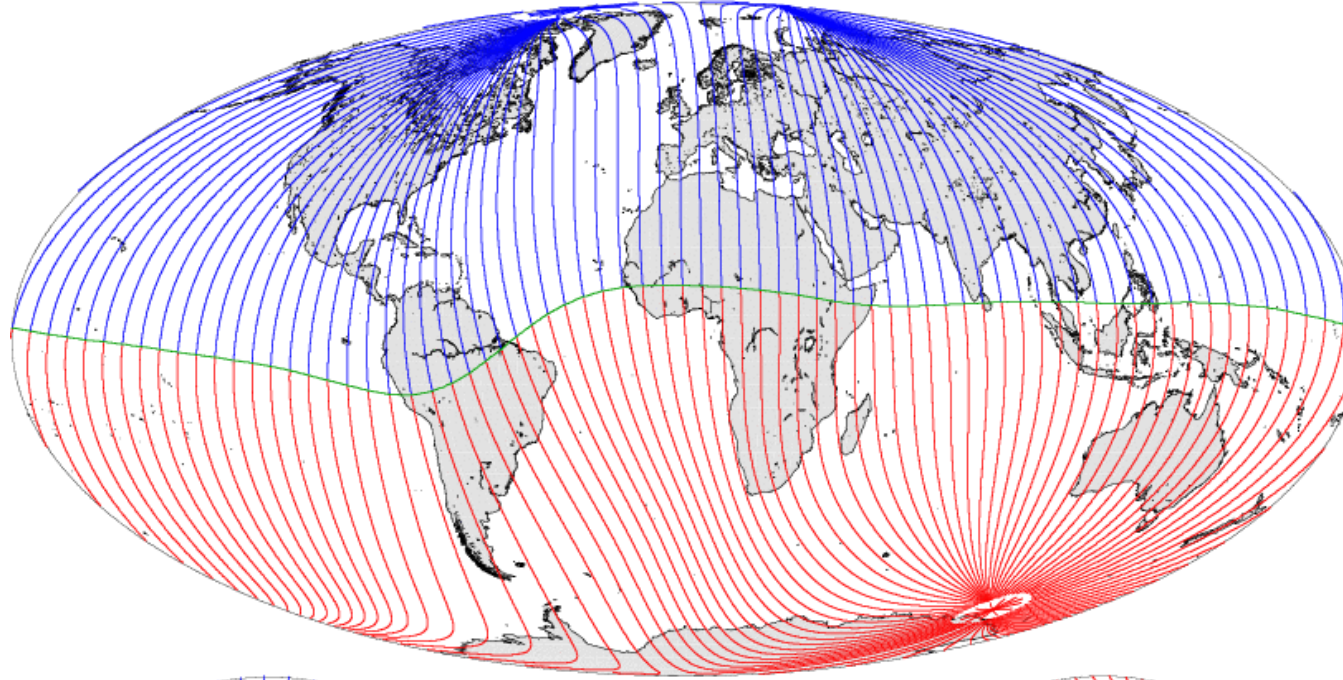
$$\mu_0 = 4\pi \cdot 10^{-7} \text{ N A}^{-2}$$

(permeability of free space)

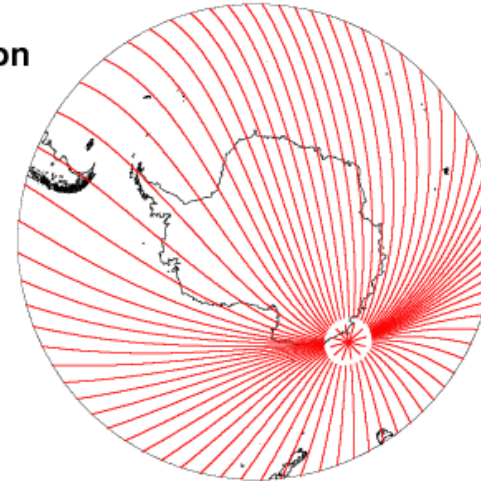
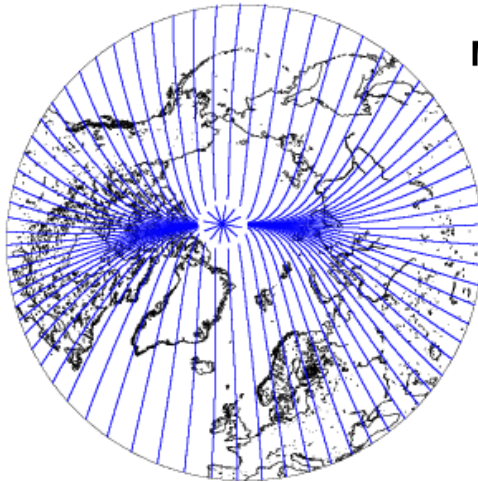


- Mapping the magnetic field of an object is simple in principle. First, measure the strength and direction of the magnetic field at a large number of locations. Then, mark each location with a vector pointing in the direction of the local magnetic field with its length proportional to the strength of the magnetic field.
- An alternative method to map the magnetic field is to “connect” the arrows to form magnetic field lines. The direction of the magnetic field at any point is parallel to the direction of nearby field lines, and the local density of field lines can be made proportional to its strength.



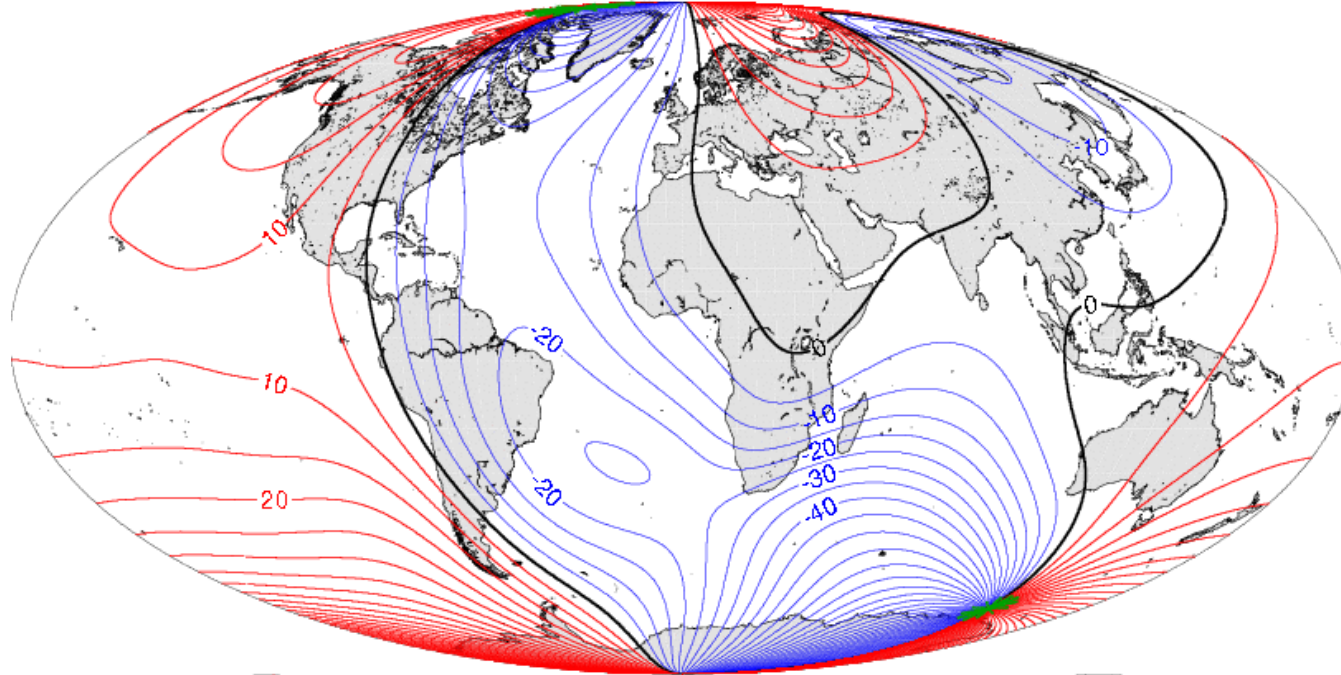


**Magnetic Field Direction
2010**

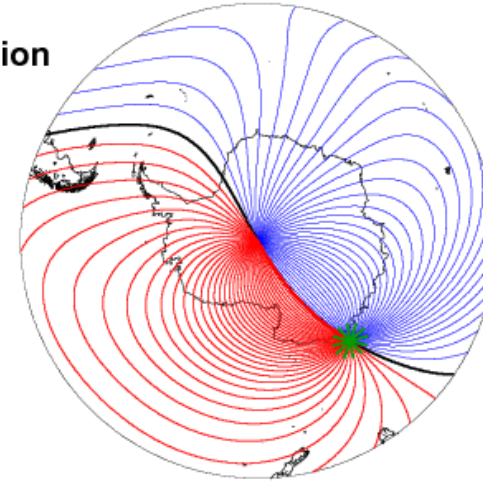
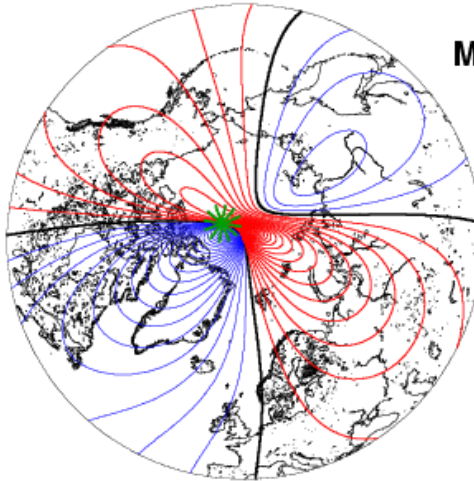


<http://geomag.org>, 2008

Horizontal direction of the magnetic field lines on the Earth's surface. The magnetic North and South poles are shown as blue and red stars, respectively. Where the lines are blue, the magnetic field dips into the Earth, where they are red it emerges from the Earth. The transition from red to blue, where the field lines are horizontal, is called the magnetic equator.



**Magnetic Field Declination
2010**



<http://geomag.org>, 2008

The difference between magnetic North and True North is called magnetic declination and is measured in degrees east (positive) or west (negative) of True North. Shown are the lines of equal declination (isogonic lines). On the black, agonic line (declination = 0) True North and Magnetic North are identical. In areas of red lines (positive declination) the compass points East of True North, and in areas of blue lines it points West of True North. The magnetic North and South poles are indicated by green stars.

The Earth's magnetic field as vectors in geographic coordinates

- To fully describe the geomagnetic field it is necessary to either measure
 - the strength and two angles of direction
 - or
 - three orthogonal components.
- The angles are declination (the deviation of the local geomagnetic field lines from geographic north) and inclination (the angle of intersection with the Earth's surface).
- Orthogonal components are commonly chosen to be X, Y and Z for the directions towards geographic north, east and vertically down, respectively.
- Geomagnetic fields are weak: the unit used to describe the geomagnetic field is nanotesla (nT), $1 \text{ nT} = 10^{-9} \text{ T}$.

Cartesian and spherical coordinates

Cartesian coordinates:

x, y, z

Spherical polar coordinates

r [km]: radius

θ [$0^\circ \dots 180^\circ$]: co-latitude

(or $\lambda = 90^\circ - \theta$ [$-90^\circ \dots 90^\circ$]: latitude)

φ [$-180^\circ \dots 180^\circ$ or $0^\circ \dots 360^\circ$]: longitude

$$x = r \sin \theta \cos \varphi$$

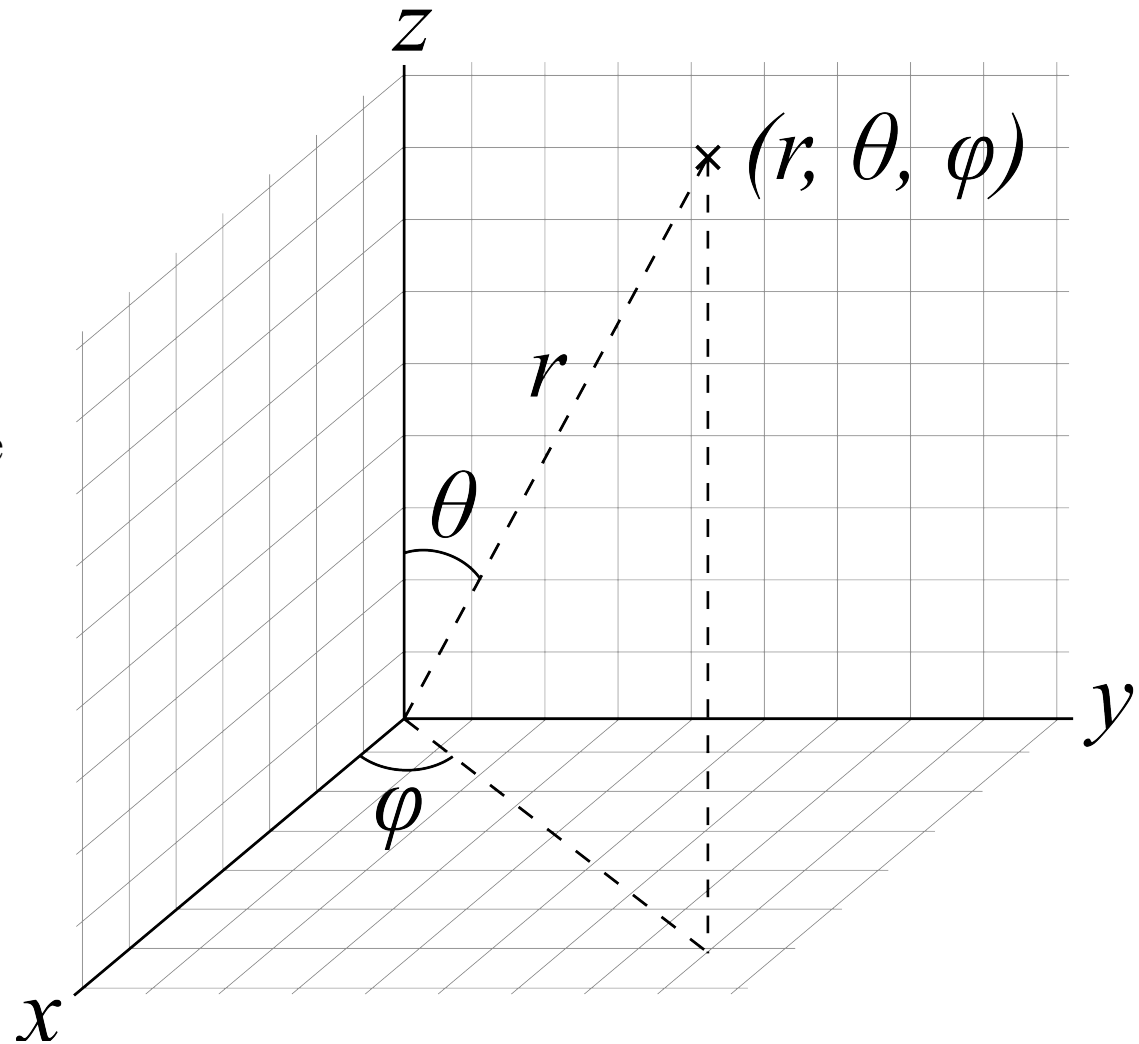
$$y = r \sin \theta \sin \varphi$$

$$z = r \cos \theta$$

$$r = \sqrt{x^2 + y^2 + z^2}$$

$$\theta = \arccos\left(\frac{z}{\sqrt{x^2 + y^2 + z^2}}\right)$$

$$\varphi = \arctan\left(\frac{y}{x}\right)$$



Position vector:

$$\mathbf{r} = x\hat{\mathbf{e}}_x + y\hat{\mathbf{e}}_y + z\hat{\mathbf{e}}_z = r\hat{\mathbf{e}}_r$$

Spherical polar unit vectors in terms of cartesian unit vectors:

$$\hat{\mathbf{e}}_r = \sin\theta \cos\varphi \hat{\mathbf{e}}_x + \sin\theta \sin\varphi \hat{\mathbf{e}}_y + \cos\theta \hat{\mathbf{e}}_z$$

$$\hat{\mathbf{e}}_\theta = \cos\theta \cos\varphi \hat{\mathbf{e}}_x + \cos\theta \sin\varphi \hat{\mathbf{e}}_y - \sin\theta \hat{\mathbf{e}}_z$$

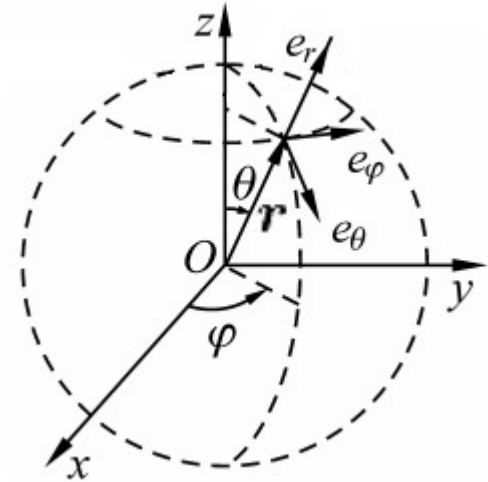
$$\hat{\mathbf{e}}_\varphi = -\sin\varphi \hat{\mathbf{e}}_x + \cos\varphi \hat{\mathbf{e}}_y$$

Cartesian unit vectors in terms of spherical polar unit vectors:

$$\hat{\mathbf{e}}_x = \sin\theta \cos\varphi \hat{\mathbf{e}}_r + \cos\theta \cos\varphi \hat{\mathbf{e}}_\theta - \sin\varphi \hat{\mathbf{e}}_\varphi$$

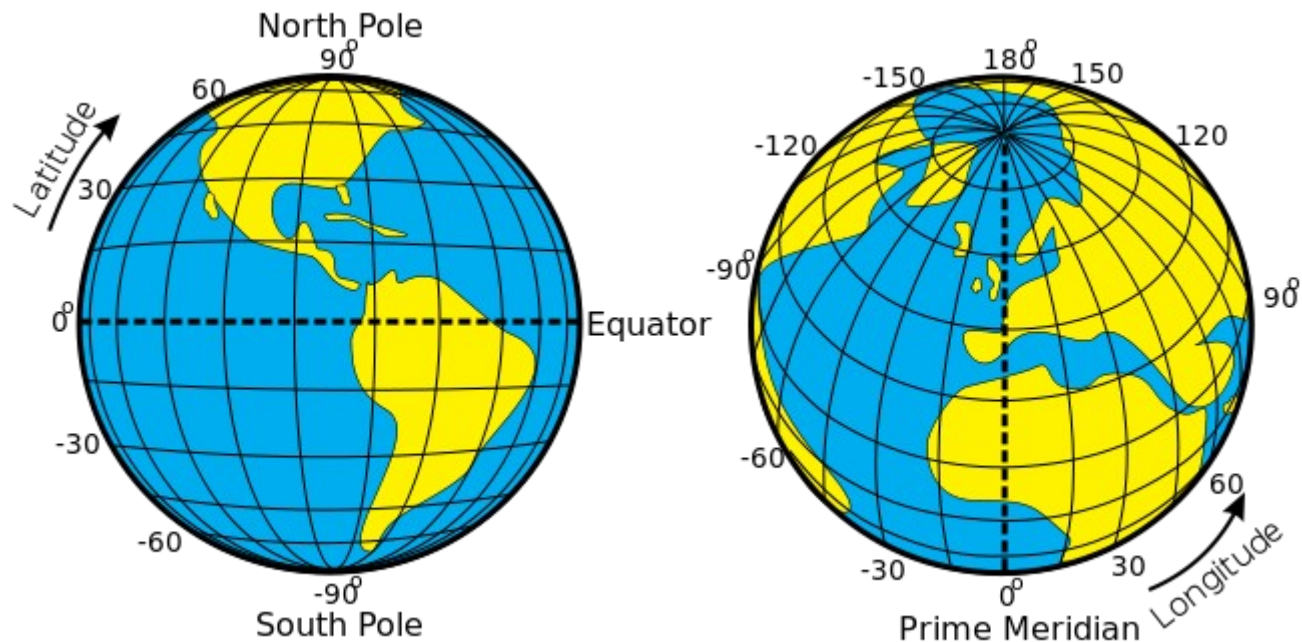
$$\hat{\mathbf{e}}_y = \sin\theta \sin\varphi \hat{\mathbf{e}}_r + \cos\theta \sin\varphi \hat{\mathbf{e}}_\theta + \cos\varphi \hat{\mathbf{e}}_\varphi$$

$$\hat{\mathbf{e}}_z = \cos\theta \hat{\mathbf{e}}_r - \sin\theta \hat{\mathbf{e}}_\theta$$



Geographic coordinates

- Geographic pole: intersection of the Earth's rotational axis and the Earth's surface
 - North pole: $+90^\circ$ or 90°N latitude
 - South pole: -90° or 90°S latitude



Magnetic field vectors in geographic coordinates

B [nT]: magnetic field vector

H [nT]: horizontal component of B

Z [nT]: vertical component of B

X [nT]: geographic north component of H

Y [nT]: geographic east component of H

D [$-180^\circ \dots 180^\circ$]: declination

I [$-90^\circ \dots 90^\circ$]: inclination

For the vectors apply:

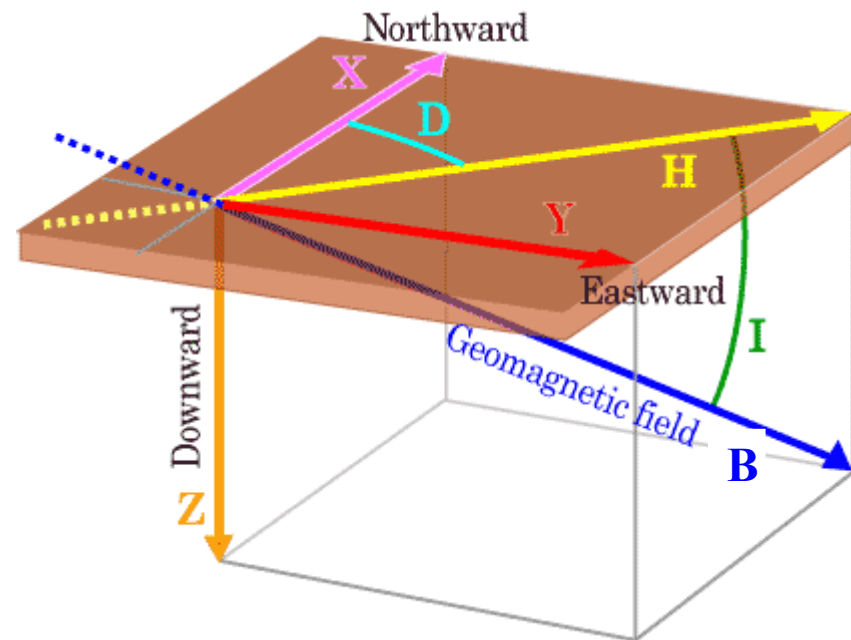
$$\mathbf{B} = \mathbf{H} + \mathbf{Z} = \mathbf{X} + \mathbf{Y} + \mathbf{Z}$$

$$\mathbf{H} = \mathbf{X} + \mathbf{Y}$$

For the lengths of vectors apply:

$$B = \sqrt{H^2 + Z^2} = \sqrt{X^2 + Y^2 + Z^2}$$

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



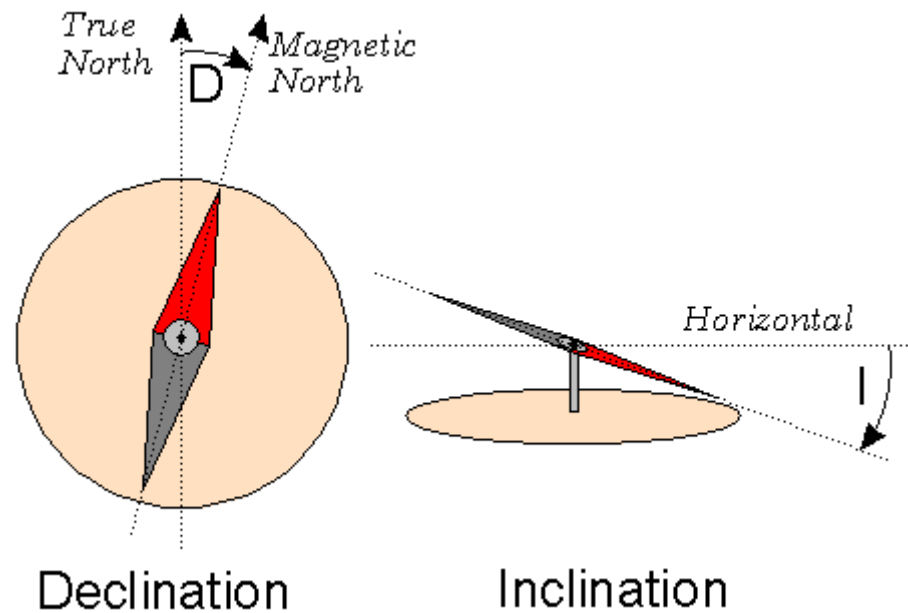
Other notations often used:

$$X = B_x = -B_\theta$$

$$Y = B_y = B_\varphi$$

$$Z = B_z = -B_r$$

- Declination is the angle between magnetic north and true north. It is positive when the angle measured is east of true north and negative when west.
- Inclination is the angle between the horizontal plane and the total field vector.



For declination D apply:

$$\tan D = \frac{Y}{X}$$

$$\sin D = \frac{Y}{H}$$

$$\cos D = \frac{X}{H}$$

For inclination I apply:

$$\tan I = \frac{Z}{H}$$

$$\sin I = \frac{Z}{B}$$

$$\cos I = \frac{H}{B}$$

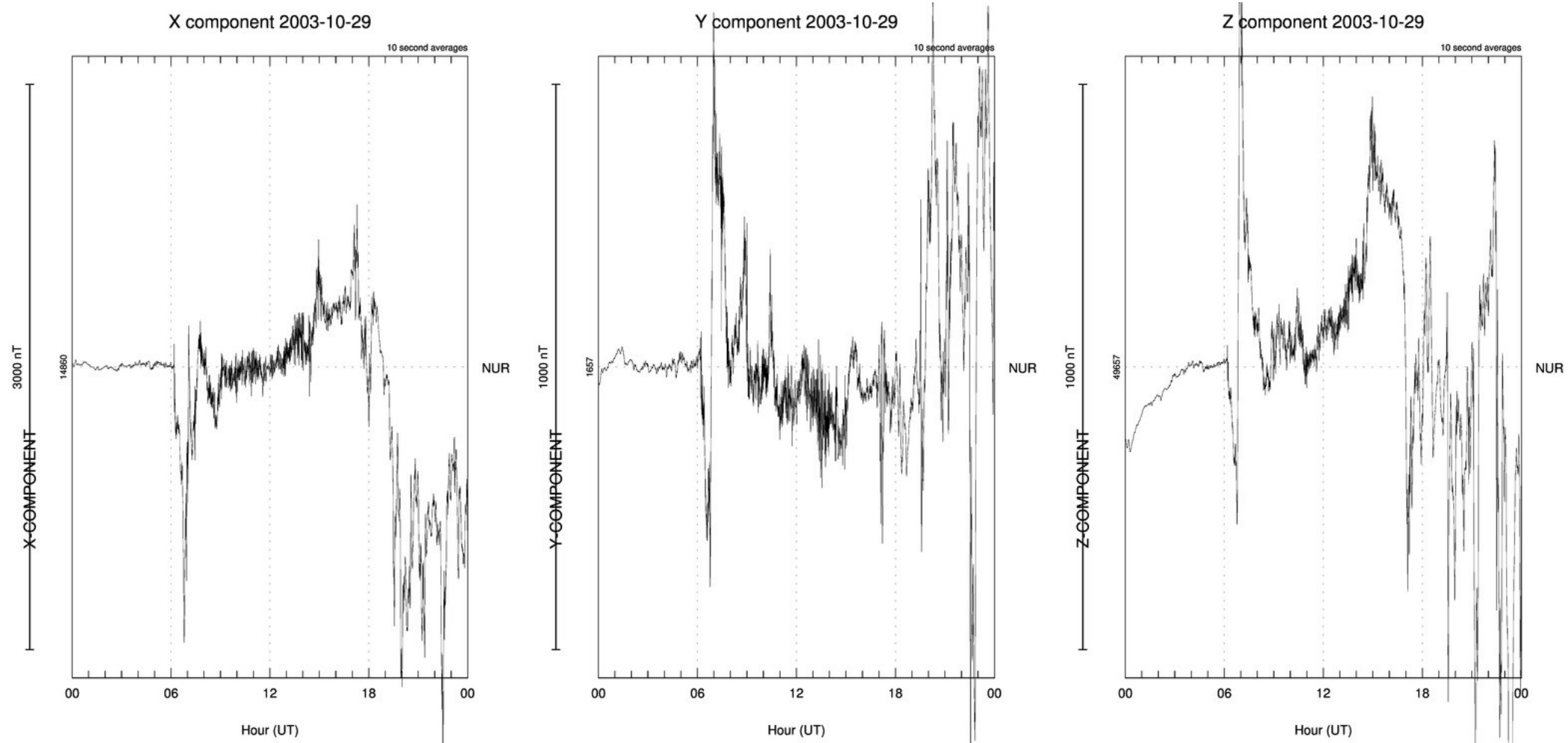
By combining the expressions for D and I :

$$X = B \cos I \cos D$$

$$Y = B \cos I \sin D$$

$$Z = B \sin I$$

Sources of the Earth's magnetic field



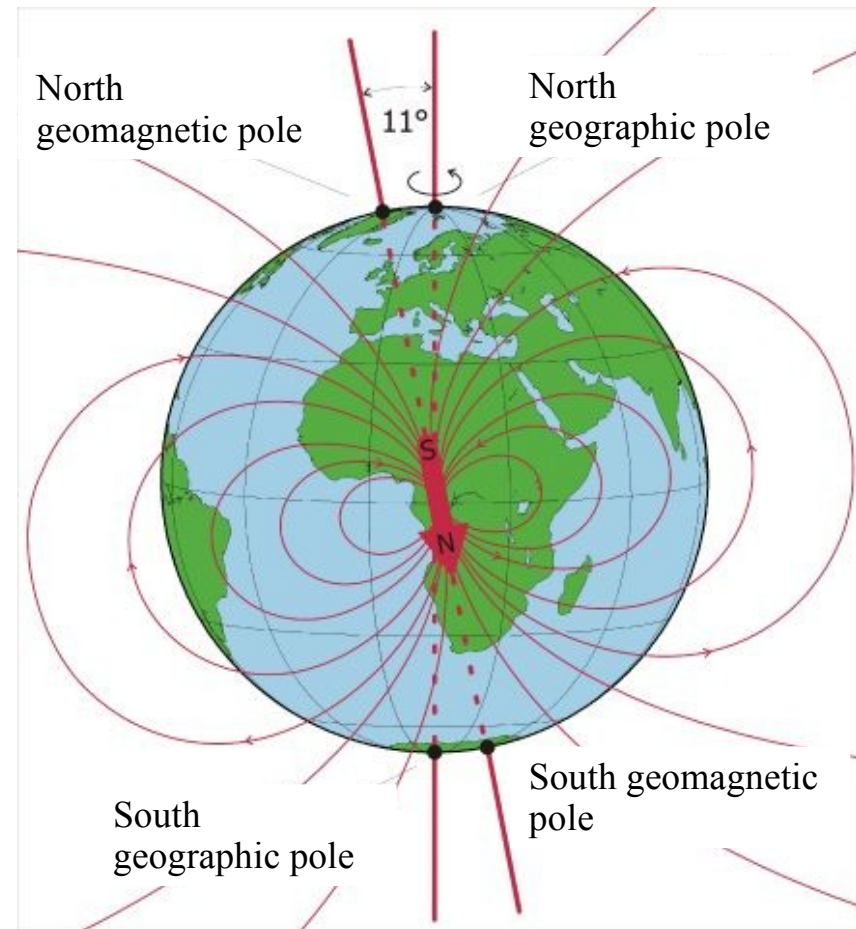
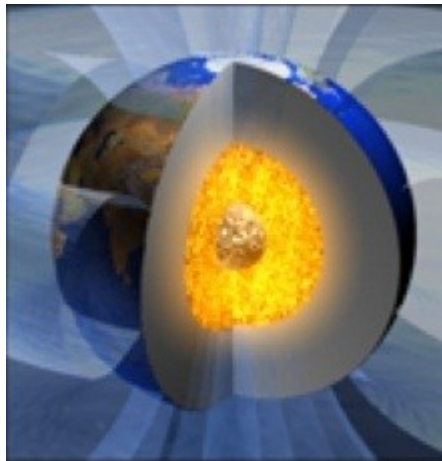
A time series of the X, Y, and Z component of the magnetic field measured at the Nurmijärvi station (60.50°N , 24.65°E).

Sources of the Earth's magnetic field

- When a measurement of the geomagnetic field is taken at any given point and time, the resulting value contains the superposition of fields having different origins and varying in magnitude:
 - core field
 - lithospheric field
 - external field
 - electromagnetically induced field.
- There are three main source regions that contribute to the Earth's magnetic field:

1. A hydrodynamic dynamo in the Earth's fluid outer core (2900-5100 km depth) produces over 99% of the Earth's magnetic field → main or core field.

- Near the Earth's surface the field is approximately like that of an imaginary bar magnet placed at the center of the Earth.
- The strength of the field at the Earth's surface ranges approximately from 30 μT at the equator to 60 μT at the poles.



2. Magnetized rocks in the lithosphere (< 50 km depth) \rightarrow lithospheric or crustal field.

- Can locally exceed the strength of the Earth's main field, but globally constitute $< 1\%$ of the field.
- Current systems inside the Earth at the depth of 2900 km cannot be expected to produce anomalies of a scale less than the order of thousands of km. The smaller ones, from hundreds of km to a few m, are of crustal origin.
- Iron in the rocks cannot be magnetized at temperatures higher than the Curie point, which is exceeded at a depth of a few tens of kilometers.
- Part of the anomalous field is caused by remnant magnetization. For example, volcanic rocks may become magnetized in the Earth's field when cooling.
- Part of the field may be caused by induced magnetization in the Earth's present field.

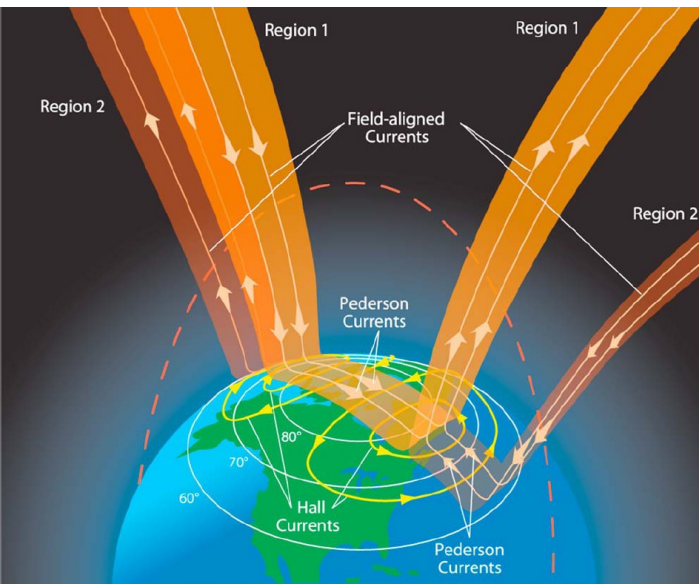


- A very strong local anomaly has been found near Kursk, 400 km south of Moscow. It is 250 km long, and composed of two parallel strips running from NE to SW. The horizontal intensity varies from 20 000 to 80 000 nT and the vertical intensity from 40 000 to 180 000 nT. The declination varies from 100°W to 60°E.
- Another strong anomaly is in Kiruna in Sweden, where the maximum value of the vertical intensity reaches 360 000 nT. The Kiruna ore is almost pure magnetite.
- An example of dangerous anomalies occurs in Jusarö in the Gulf of Finland, where the anomalous part of the field is over 60 000 nT and where the disturbances in declination have caused several shipwrecks.
- Very local anomalies of a similar strength can be found in many areas. Sometimes the dimensions can be just a few meters if there is a boulder containing much magnetite close to the surface.

3. Electric currents in the near-Earth space (> 100 km altitude) \rightarrow external magnetic field.

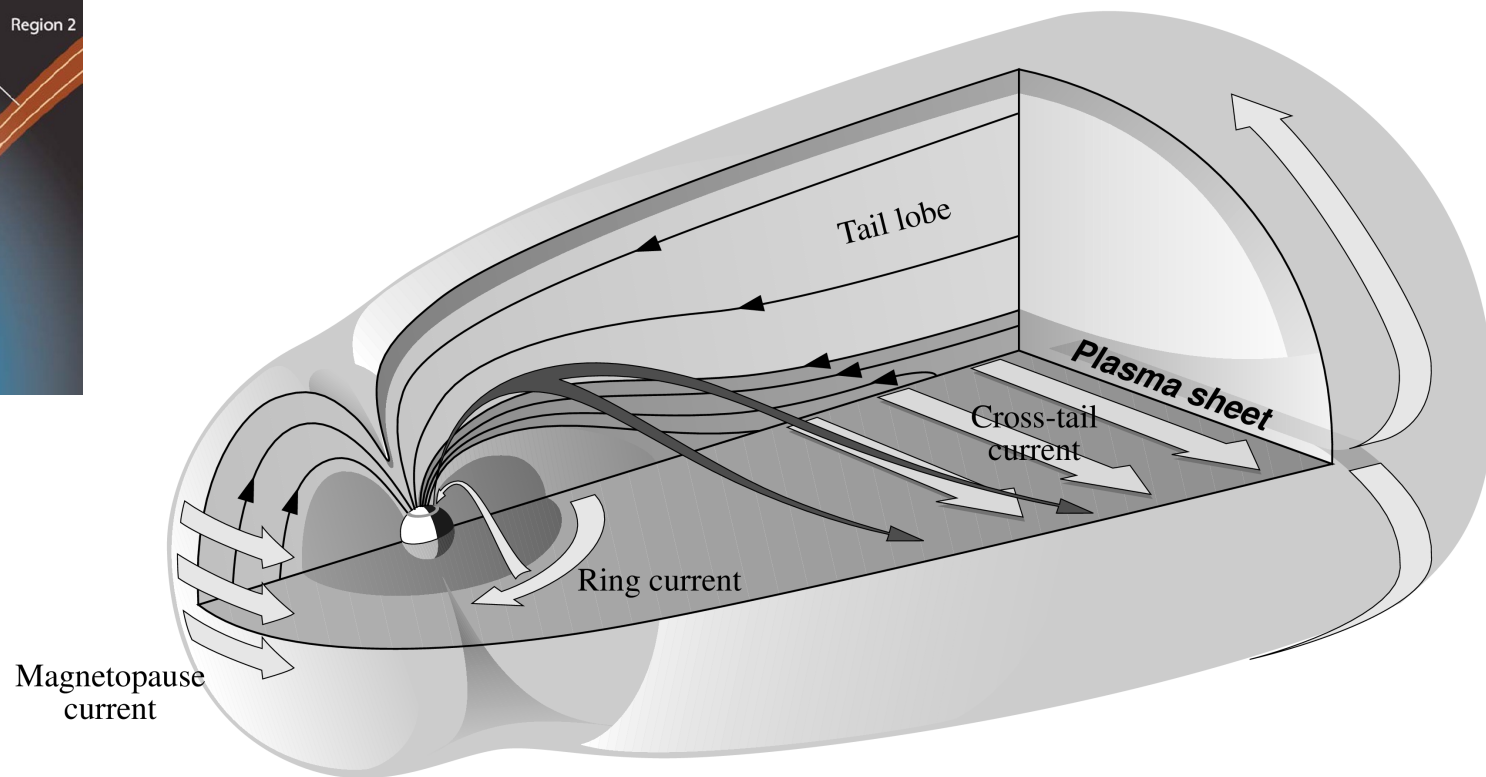
- In an annual average of a measured time series of the magnetic field, the external contribution is $< 1\%$.
- During magnetic storms, the external contribution can be up to several percent of the main field, for a few hours.

Current systems in the ionosphere:

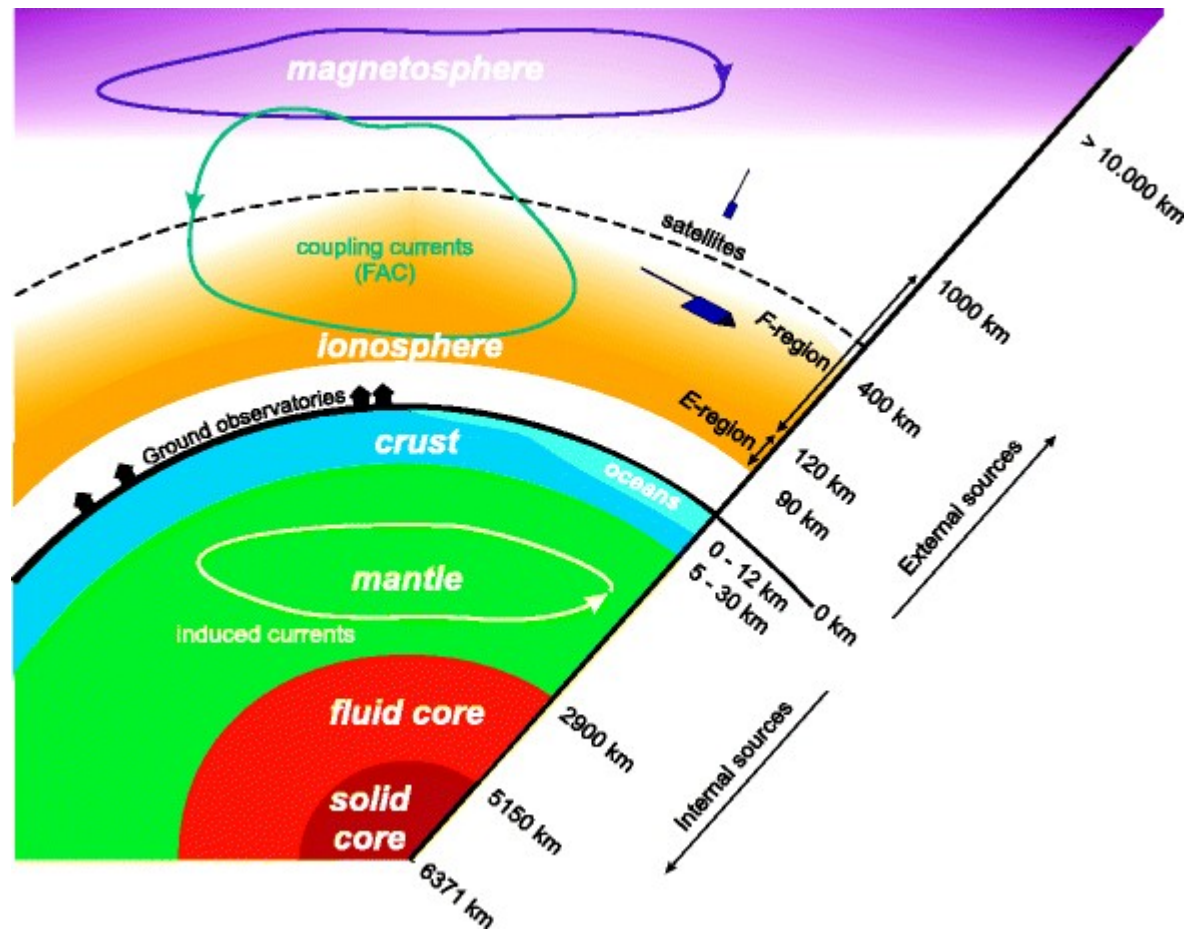


(Btw, it's Pedersen,
not Pederson!)

Current systems in the magnetosphere:



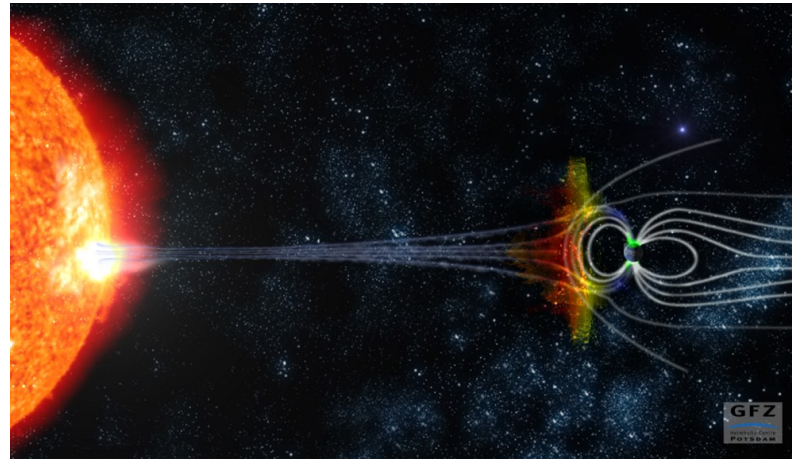
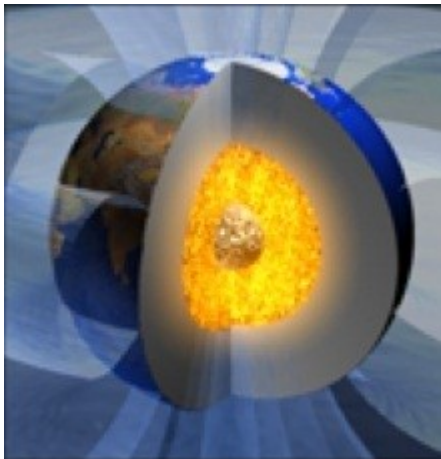
Sources of the Earth's magnetic field



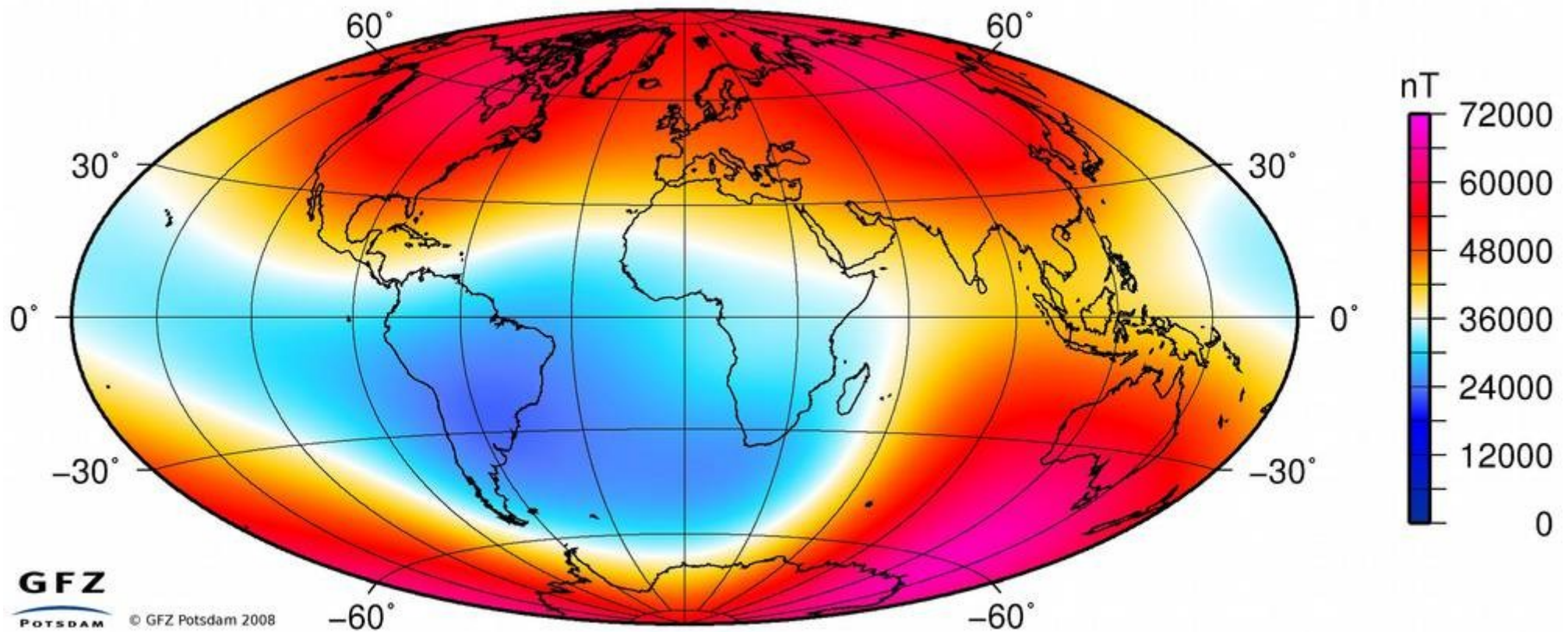
- One of the very few ways of probing the Earth's liquid core is to measure the magnetic field it creates and how the field changes over time. Variations in the field directly reflect the flow of fluid in the outermost core.
- The continuous changes in the core field result in the motion of the magnetic poles and the magnetic reversals.
- The changes of the core field are important for the study of the Earth's lithosphere. The crustal field has an induced and a remnant magnetized part. The latter depend on the magnetic properties of the sub-surface rock and the history of the Earth's core field.

Temporal variations of the Earth's magnetic field

- There are two types of temporal variations in the Earth's magnetic field:
 - Transient variations
 - Irregular variations with periods from seconds to hours.
 - Caused by electric currents in the near-Earth space (> 100 km altitude) that are driven by solar activity.
 - Secular variations
 - Changes in the Earth's magnetic field on time scales of about a year or more.
 - Caused by changes in the strength and direction of the electric currents in the Earth's liquid core at 2900-5100 km depth.

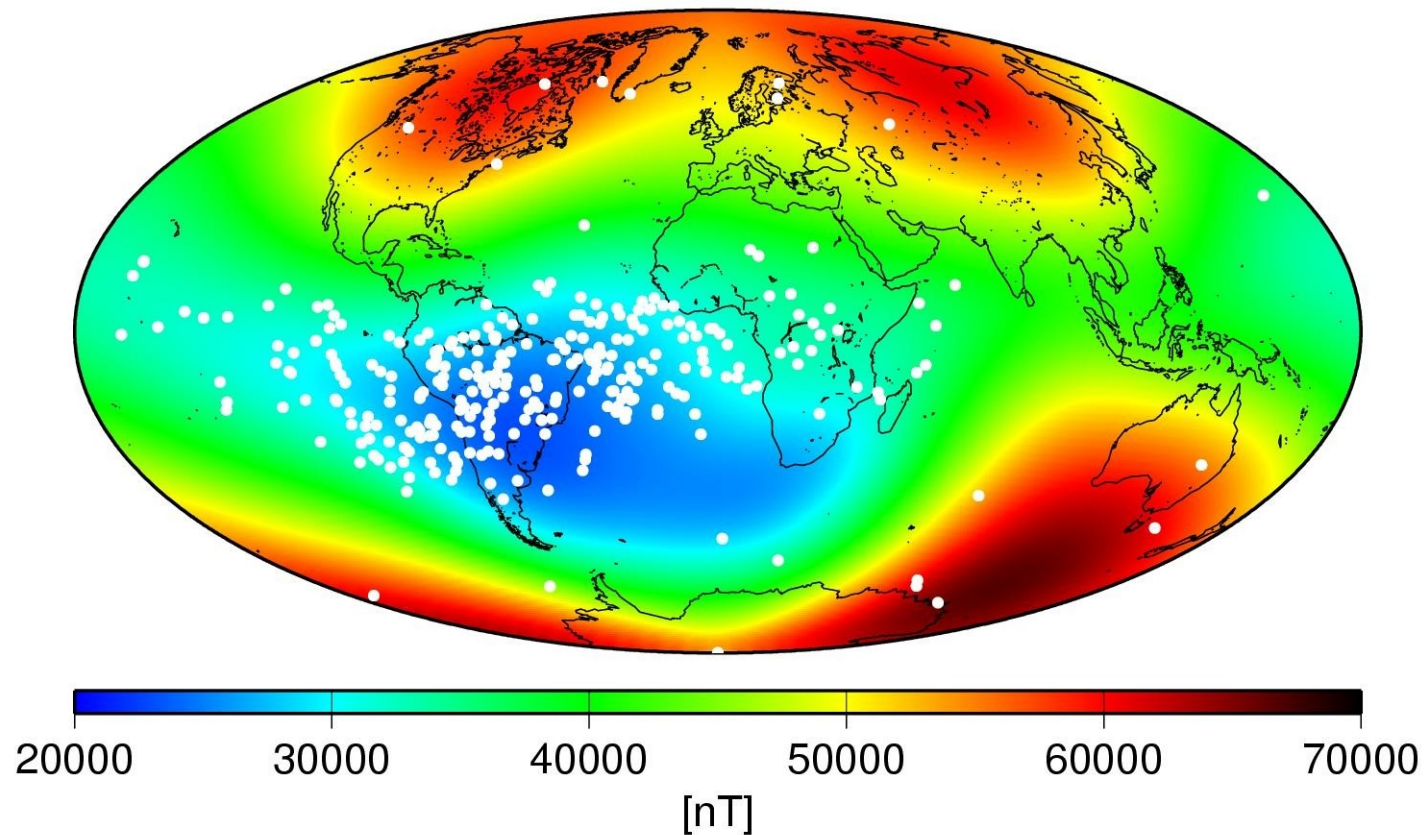


An interesting feature of the core field is the so-called South Atlantic Anomaly: a large area of very low field intensity (less than 20 000 nT) over South America, the southern Atlantic and southern Africa.



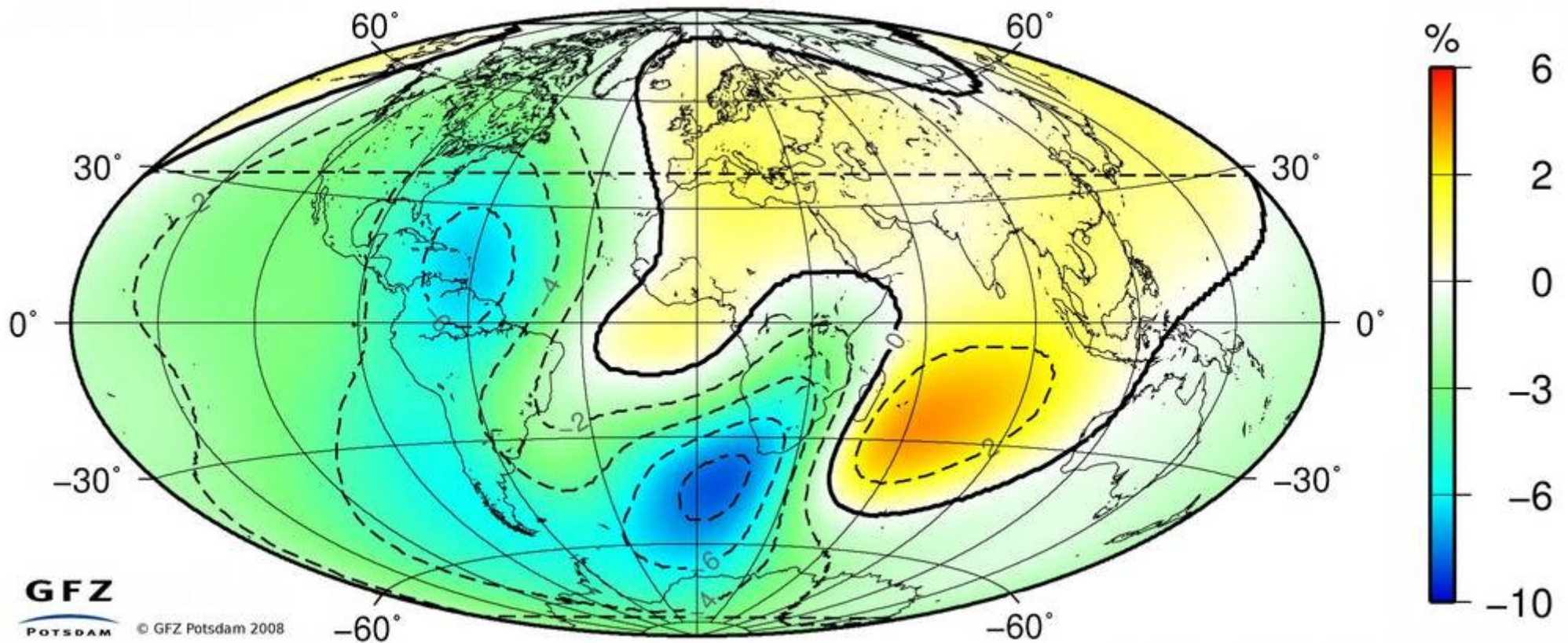
Magnetic field intensity at the Earth's surface according to the GRIMM model for epoch 2005.0. The model is calculated using data from the CHAMP satellite and magnetic observatories.

The South Atlantic Anomaly is an area where the magnetic field is particularly weak – in fact, it is only half as strong as in Europe. This is problematic for satellites orbiting Earth, and the majority of technical faults occur when they pass through this region.

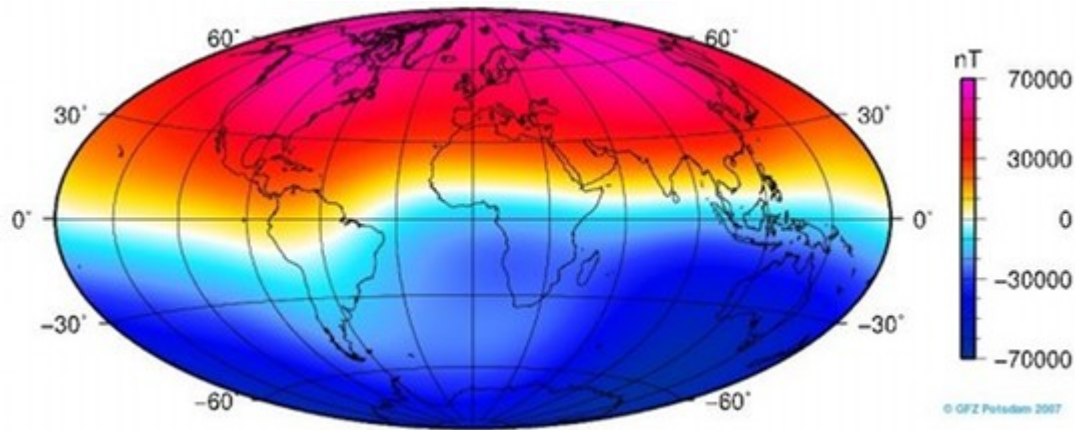


The white spots on this map indicate where electronic equipment on a satellite (TOPEX/Poseidon) was affected by radiation as it orbited above.

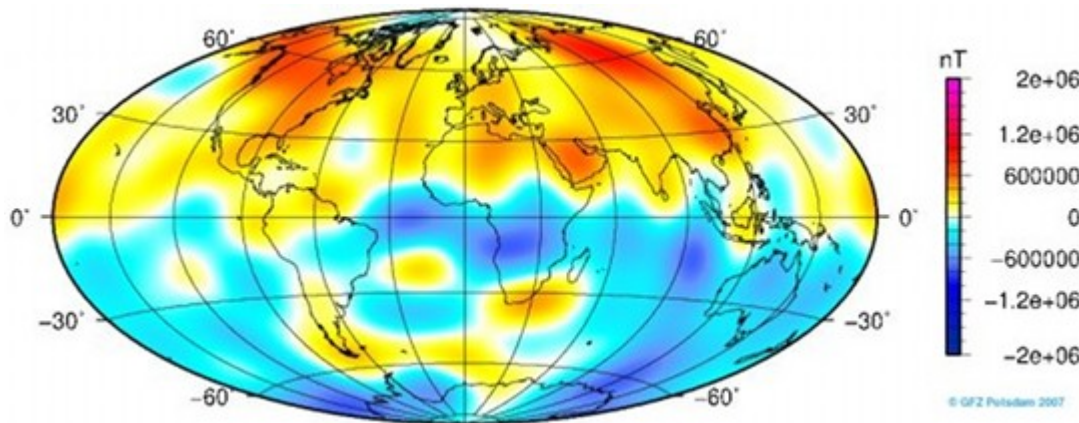
MAGSAT (1980) and CHAMP (2005) data show that the magnetic field of the South-Atlantic anomaly has been decreasing by some 10% during the past 25 years.



The percentage change of the geomagnetic field intensity from 1980 to 2005, as determined by the MAGSAT and CHAMP satellites.

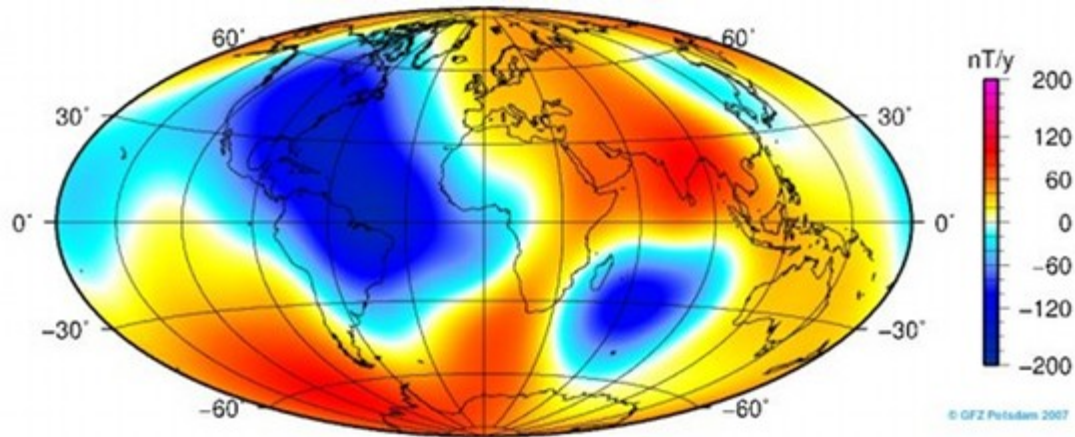


Vertical component of the magnetic field at the Earth's surface.

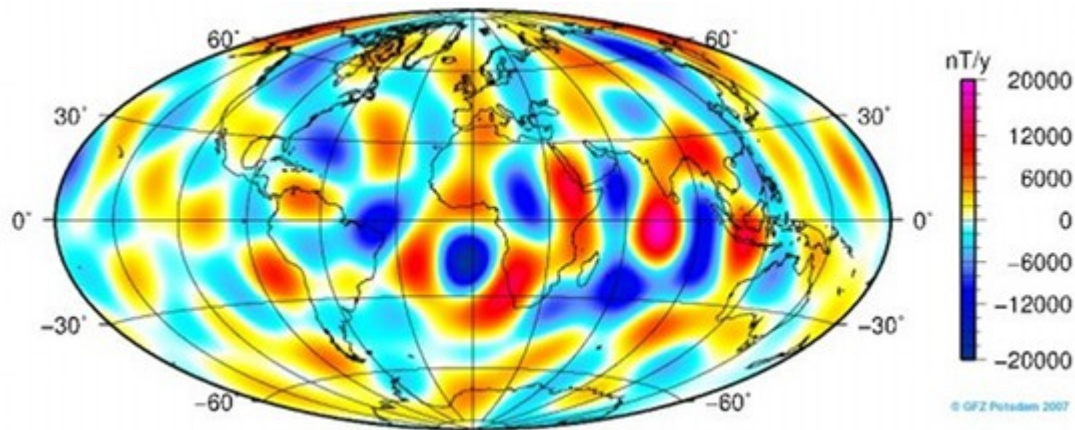


Vertical component of the magnetic field at the core-mantle boundary.

Distinct patches of reversed magnetic flux at the poles and below Africa can be identified, which could be related to the present day field decrease. The most prominent feature in this respect is the growing patch of reverse magnetic polarity beneath South Africa.

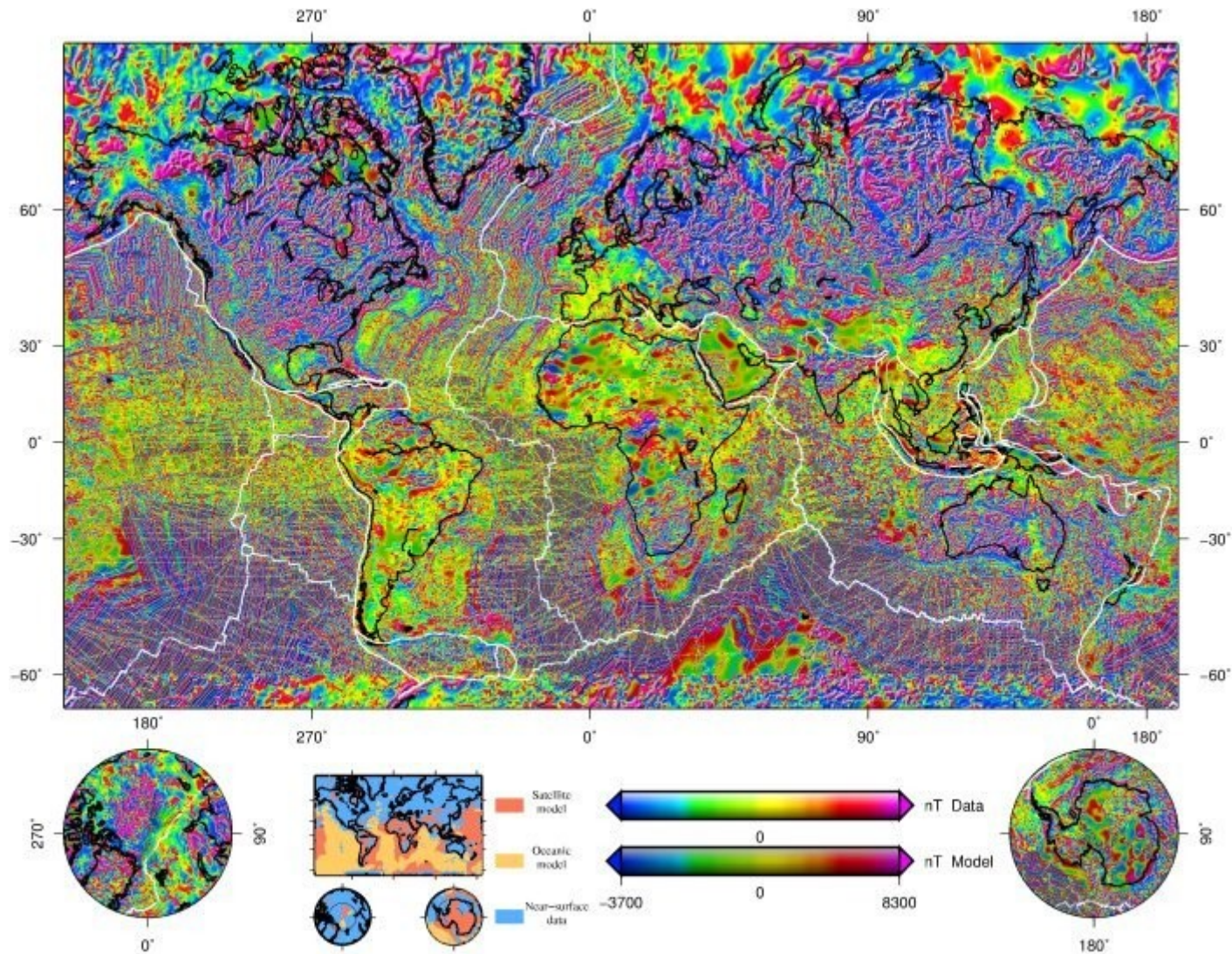


Secular variation of the vertical component of the magnetic field at the Earth's surface.



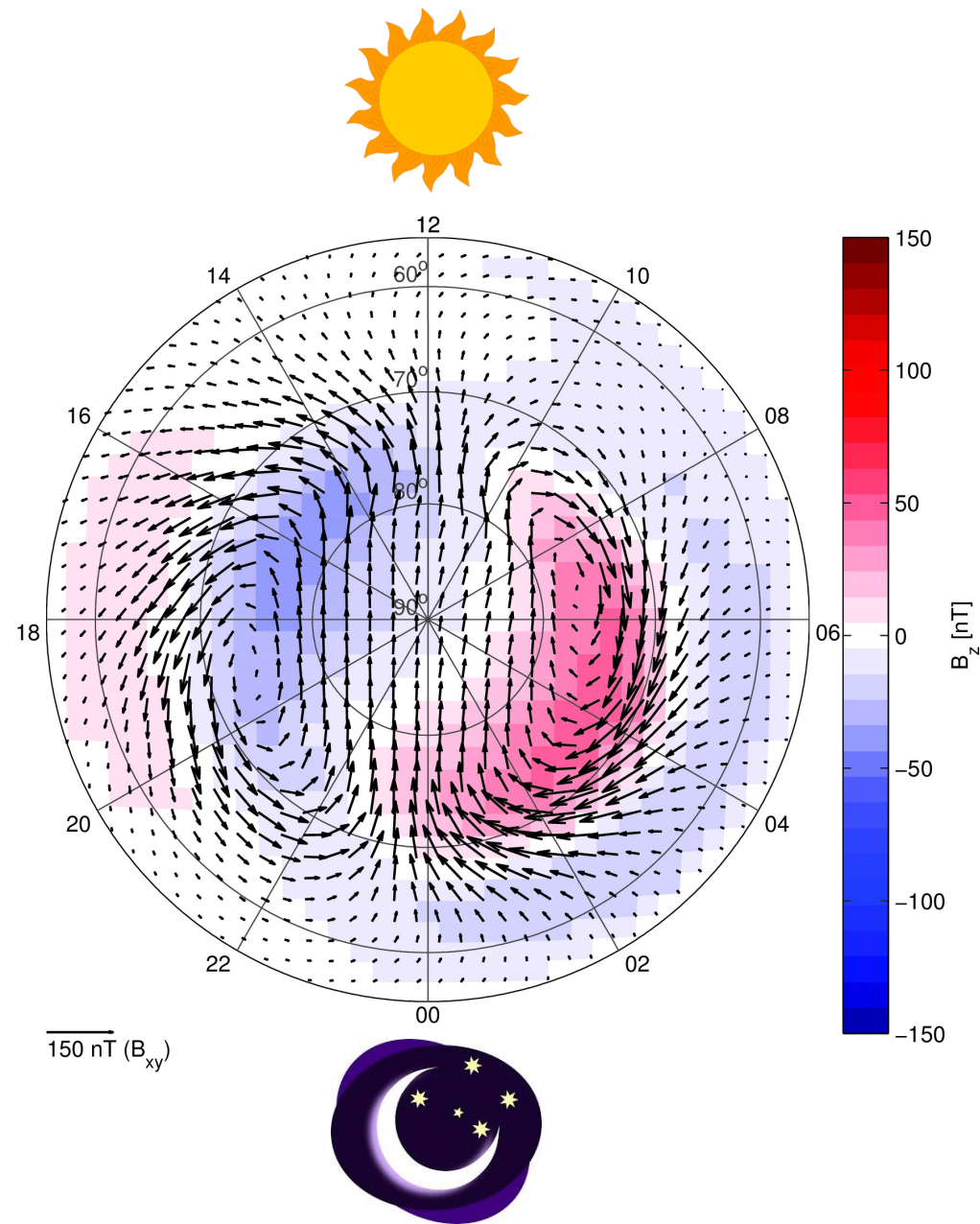
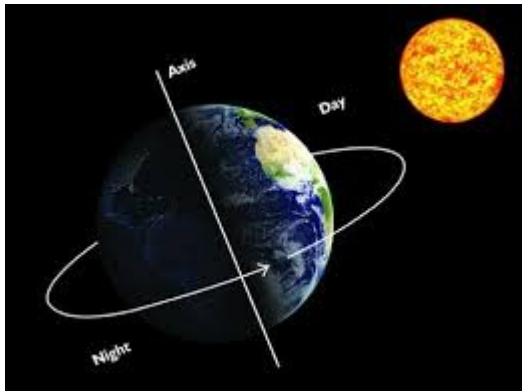
Secular variation of the vertical component of the magnetic field at the core-mantle boundary.

The core field is subject to temporal variations, known as secular variation. The magnetic field does not change uniformly over the Earth. While the overall strength of the dipole field is decreasing, there exist a few regions where the field strength is increasing.



World Digital Anomaly Map (WDMAM 2007). Worldwide distribution of anomalies in the magnetic lithosphere.

- In the hands of experienced geophysicists, maps of anomalies of the magnetic field tell about the geological structure of the crust.
- Combined with other geophysical and geological information, the magnetic data may lead to the finding of profitable ores.
- Therefore, aeromagnetic surveys are commonly carried out in most areas of the world. The whole area of many countries have been surveyed.



Average magnetic field caused by ionospheric currents from the CHAMP satellite data (2000-2010) at ~350 km altitude around the north magnetic pole.