NATURE OF EARTH'S MAGNETIC FIELD AND ITS APPLICATION FOR COMMERCIAL FLIGHT NAVIGATION

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Abstract. This article presents properties of the Earth's magnetic field and its impact on the commercial flight navigation. Scientific studies of the Earth's magnetic field in Slovenia during the last thirty years are presented. This paper deals with theoretical research regarding the magnetopause that protects life on Earth from lethal radiation from space. Changes in the Earth's magnetic field have been measured and are presented. The magnetic compass, which operates uses the Earth's magnetic field, is the oldest navigation instrument. Through centuries it has been the most important aid to navigation on the sea, helping seafarers to steer the right courses. Other physical measurements are not as easy or reliable as measurements by magnetic compass. Today, the magnetic compass is still the basic navigation instrument on ships and aircraft. It is used in exceptional cases when radio navigation systems do not operate reliably.

Keywords: Earth's magnetism, magnetic compass, aeronautical navigation

1. Description of the Earth's Magnetic Field for Future Navigators

The Earth's magnetism has been researched longer than any other natural phenomenon and has had the greatest number of differing explanations. Ancient nations used a magnetic needle, which could rotate freely around its vertical axis, for navigation and geodesy. The ancient Chinese people

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were acquainted with magnetic inclination. In their opinion this inclination was the connection between the earth and the sky[1]. An explanation of how and why the Earth's magnetic field is generated got its final form in modern times when the astronomical and geophysical researchers resolved how sunspots and the Sun's magnetic field came into being. Their theory was verified with considerable help from spacecraft in the second half of the last century.

William Gilbert started modern research into the Earth's magnetism and published his findings in 1600[2]. Measuring the Earth's magnetism was done mainly by seafarers during the seventeenth and eighteenth centuries (Figure 64). They measured the directions and size of the magnetic forces that originated from the Earth. They first drew compass maps for the entire surface of the Earth with all the anomalies they noticed. They indicated the central magnetic field source in the form of a magnetic dipole. The same conclusions were reached by Carl Friedrich Gauss and Wilhelm Weber[3], whose findings were based on measurements and theoretical research in 1836 – 1841. Analyses of volcanic rocks from the edges of tectonic plates in the oceans, done during the 1960s, showed that the Earth's magnetic dipole reverses its polarization each half million years on average[4]. Why the Earth's magnetic poles reverse has not yet been determined.

Dutch physicist Pieter Zeeman found in 1897 that a strong magnetic field may change spectral light lines[5]. Such changes grew in proportion to the density of the magnetic field. This conclusion resulted in the enhancement of measuring methods, so that it became possible to measure the magnetic field of sunspots and the Sun. The Sun's magnetic field changes its direction cyclically about every eleven years.

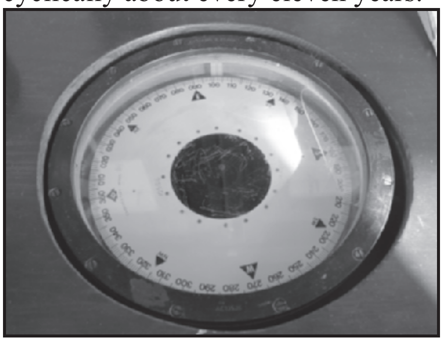

Figure 64. Liquid magnetic compass on the vessel.

In 1919, Sir Joseph Larmor explained how sunspots developed. Based on an electric dynamo principle, according to his explanation, an electric current emerges in the Sun's plasma. The electric current generates a magnetic field which, in turn drove the electric current. The discovery, by astronomers, that the Sun does not rotate as a solid was important. The

Sun's equator rotates fastest, and the velocity of rotation decreases towards its poles. Therefore, the Sun can act as a self-stimulated electric dynamo. A useful theoretical explanation on the basis of these findings was introduced by Stanislav Braginsky in 1964. He assumed that the magnetic field was axially symmetrical with small asymmetries[6]. Because of the heat, the plasma flowed towards the surface. The origin of the heat has not been completely explained. The straight-line movement of the plasma towards the surface turned into rotation because of the Coriolis acceleration. It appeared because the reference frame was moving and therefore the whirling was stronger in the direction of rotation. Such asymmetries are also expected in the Earth's fluid core. Electric currents, which cause the Earth's magnetic field, are the result of the different speeds of stratum rotation of the three basic layers: solid core, fluid magma and solid outer crust.

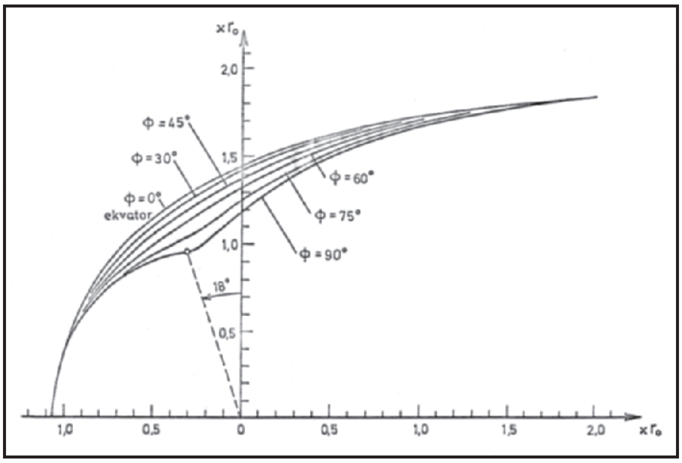

Figure 65. Results of calculation of Earth magnetopause cross-section shape at different angles Φ with regard to the half-meridian plane Φ = 90°.

2. Influence of the Solar Wind on the Earth

In 1896, Norwegian physicist Kristian Birkeland proved, on the basis of laboratory tests, that the Northern Lights are the results of electrified solar particles colliding with the Earth's magnetic field. The phenomenon of there being less space radiation when the Sun's activity is greater was explained in 1952 by Swedish physicist, Hannes Alfvén[7]. He proposed that the Sun's magnetic field was in direct proportion to the density of its radiation. The stronger the Sun's magnetic field, the more efficient it was in deflecting galactic space radiation. In 1953 Eugen Parker, an English physicist, found that the Sun's corona was not a static phenomenon but that it spread through space in the form of the solar wind[8].

The solar wind, composed of hydrogen nuclei and electrons, spreads through space at a speed that increases as the wind's distance from its source increases. When it reaches the Earth, it is deflected by the Earth's magnetic field and therefore splits into two flows, a proton flow and an electron flow, which will whirl in opposite directions. They make a curved crossing almost parallel to the Earth's surface, and then disperse and fly off into space[9]. The currents that appear around the Earth during this phenomenon make the Earth's magnetic field stronger in the direction towards the Earth and weaker in the direction away from the Earth. The stratum where the magnetic field decreases to zero is on the sunny side at a height of 100 km above the Earth and is called the Magnetopause. This stratum isolates the Earth from the destructive impact of space radiation and by doing so protects life on the Earth.

3. Research into the Earth's Magnetism in Slovenia

In the 1970's the Faculty of Electrical Engineering in the University of Ljubljana carried out comprehensive theoretical research on the magnetosphere[10]. Based on the fact that the solar wind always blows comets' tails away from the Sun, it was assumed that the magnetopause was teardrop shaped with its tail turned away from the Sun. The research started with a magneto-hydrodynamic equation for the pressure of the solar wind (1.1).

$$grad\,\overline{p} = \overline{J}\; x\; \overline{B} \tag{1.1}$$

where:
p = solar wind pressure
J = density of the solar wind flow
B = density of the Earth's magnetic field

In the Earth's magnetopause it is possible to use the equation (1.1) of uniform part-flow in a form where the mechanical pressure of the solar wind is equal to the Earth's magnetic-field effect. By using an iteration calculation procedure according to the Newton – Raphs method, researchers came to the conclusion that the bipolar magnetic field on the sunny side of the Earth is rather deformed (Figure 65). Based on additional results, which were reached at the same time by other research groups, the magnetopause was given a shape like a teardrop with a tail, on the opposite of the sunny side of Earth. This shape was confirmed by measurements carried out by spacecraft. Theoretical research and measurements verified that the Earth's magnetic field does not spread into space.

In the last fifteen years, the Laboratory for Magnetic Measurements at the Faculty of Electrical Engineering in the University of Ljubljana has systematically researched changes in the Earth's magnetic field in different settings. First, researchers were interested in Changes to the Earth's magnetic field caused by plants. Measurements verified that plants impact the local magnetic field, at a micro-level in different ways depending on their states and inner processes[11], and that the strength of the magnetic field impacts plant growth, both in plantations and in forests (Figure 66)[12].

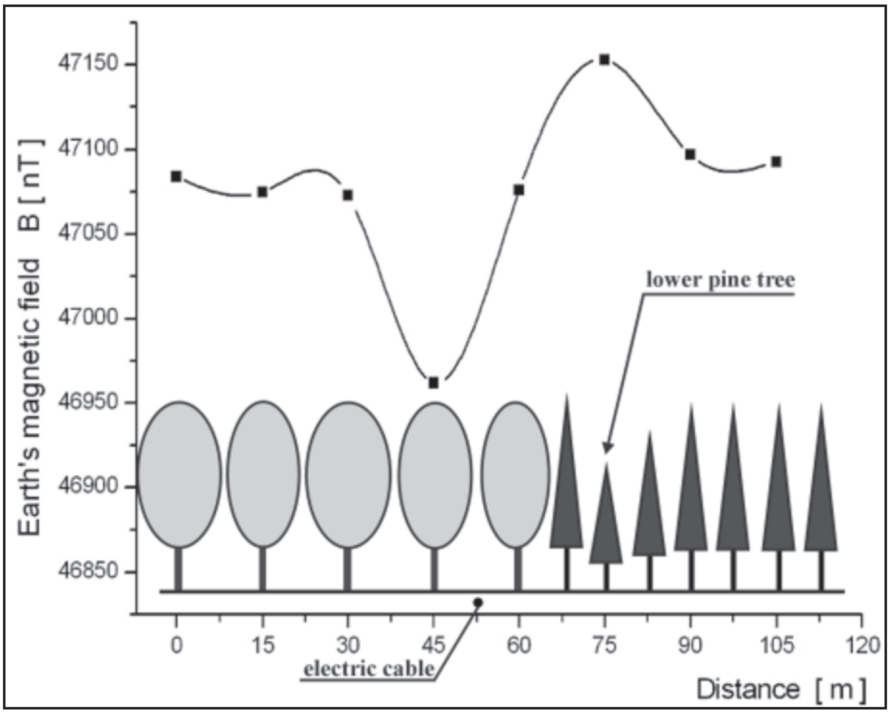

Figure 66. Impact of increase in gradients of the Earth's local magnetic field on the growth of young pine trees.

Changes in the Earth's magnetism in residential areas and at archaeological sites were also of interest. In both cases, there were large-scale changes of gradients, particularly in the vicinity of ferromagnetic materials. Especially large deviations from normal levels of magnetism were measured indoors, in residential buildings constructed of reinforced concrete with branched electrical installations[13]. However all values were below the approved limits in accordance with the valid regulations. Measurements indicating changes in the Earth's magnetic field in non-residential areas were also of interest. Changes were observed during weather changes and during different kinds of storms (Figure 67).

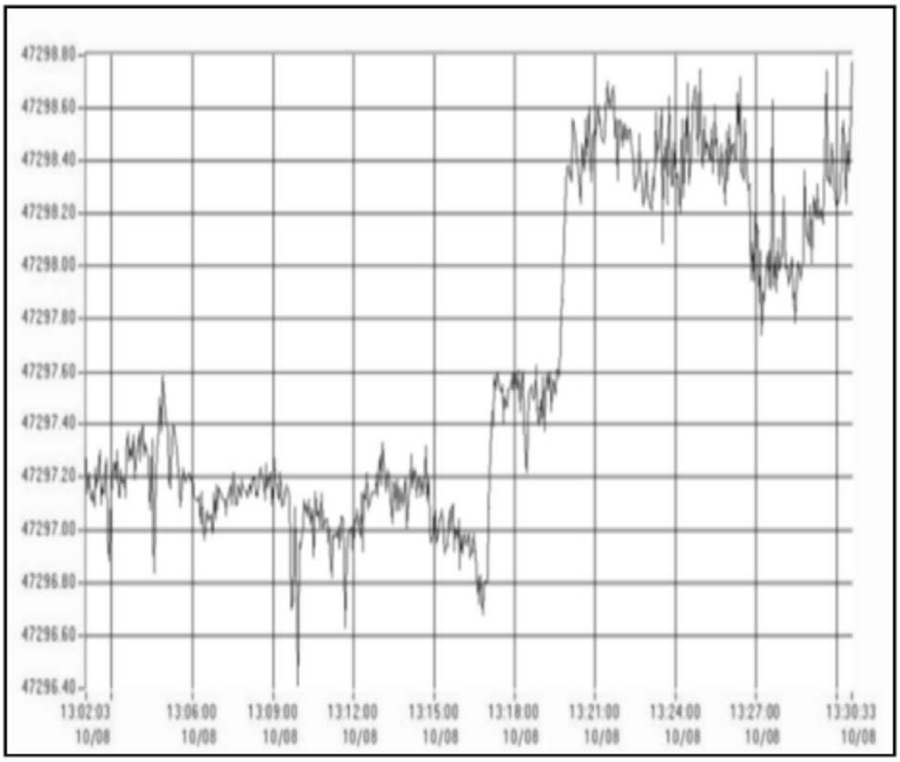

Figure 67. Changes in the Earth's magnetic field at a location with small deformations while the weather was changing and before the rain started.

4. Aeronautical Navigation by the Use of the Magnetic Field

Navigation is a method for planning a journey from one place to another safely and in accordance with given conditions. In its basic meaning, navigation is the art and science of planning, controlling, and piloting a vessel from its starting place to its destination. Man improved navigation methods several thousand years ago, some sources have even said 8,000 years ago, to such a level that it became a science [14].

Navigation means recognising the place where one finds oneself and determining the time necessary to reach a particular destination. The most basic type of navigation is called Dead Reckoning. It is also the most demanding. Ancient Phoenicians used this type of sea navigation when visibility was poor. Today, it is still used as an independent method of navigating, but most often it is used as an additional instrument to other methods of navigation (terrestrial, astronomic, radio-navigation) and as a check on other types of navigation. New positions can be defined on the basis of the known direction and speed of movement as well as on the basis of the position previously reached. For a safe journey, the following navigation parameters must be calculated: current position, distance to destination, travelling speed and direction, current fuel consumption and quantity of fuel needed, and the time left for the rest of the journey[15]. Because of the number of unknowns in such a method of calculation, the accuracy range for defining a position is ±1/8 of the route already travelled. Before the introduction of the satellite navigation system, Dead Reckoning navigation was the only way to navigate on the open sea or in the air where all other methods failed.

The magnetic compass is a useful navigation instrument that must be calibrated prior to use, as its frame may cause magnetic deviation. The magnetic declination should be added to the adjusted magnetic heading (the deviation of magnetic North from true North), at any single position on the globe. Easterly declination is a negative quantity and westerly declination is a positive quantity. The necessary correction can be made by adding the declination to True North. The North Pole is the appropriate reference point for maps, but finding its precise position is rather difficult. So it can only be a useful reference point for course control together with the magnetic pole. However, in the case of aeronautical navigation, a true flight course can be defined only with additional consideration of the wind correction angle (Figure 68). The heading is obtained when wind correction angle is applied to a True Course. When wind is blowing from the left a negative wind correction is added and when wind is blowing from the right a positive correction is added. For a flight plan worksheet, all these influences are taken into consideration as a matter of course, and the flight log is drawn up in accordance with them (1.2).

In exceptional cases, the Dead Reckoning method may be used for IFR (Instrument Flight Rules) in civil air navigation. In the cases of flights over very remote places and seas, where all other ways of navigation are unusable, unavailable, or do not operate reliably, the pilot must be prepared to use this kind of navigation. Before taking off, the flight speed and wind correction angle have to be carefully calculated. After take off, the wind influence in the upper air strata should be closely estimated. Dead Reckoning is used rarely, but it is the most appropriate kind of navigation for covering gaps between areas that use different kinds of aeronautical navigation.

$$TC + WCA + VAR + DEV = CH \tag{1.2}$$

Sign	**Meaning**	**Influence**
TC	True Course, line drawing on a map	
WCA	Wind Correction Angle	left -, right +

Sign	Meaning	Influence
VAR	Variation	East -, West +
DEV	Deviation	-, +
CH	Compass Heading	

The last resort for a pilot who has lost electric power or has had a fire in the cockpit is Dead Reckoning. In these cases he has only a magnetic compass, a clock, and an airspeed indicator. Errors in Dead Reckoning depend on the accuracy of available data before beginning calculations. During emergency situations a pilot will follow the magnetic compass heading to the point of destination. For a new course and speed of flight he should also coordinate already known data on wind direction. He should assure himself that there are no high-rising barriers in his course. The experienced pilot will try to reach good visibility quickly, to reduce the possibility of collision. The pilot plans a new flight course with the following conditions; beginning the visible part of the route with the best conditions for landing, the flight time and the time before fuel runs out. The pilot should observe flight speed and time simultaneously, and not panic. To prevent flying around in circles, the MPP (Most Probable Position) position should be observed at regular intervals. The MPP observation is the only way to prevent circling in emergency situations.

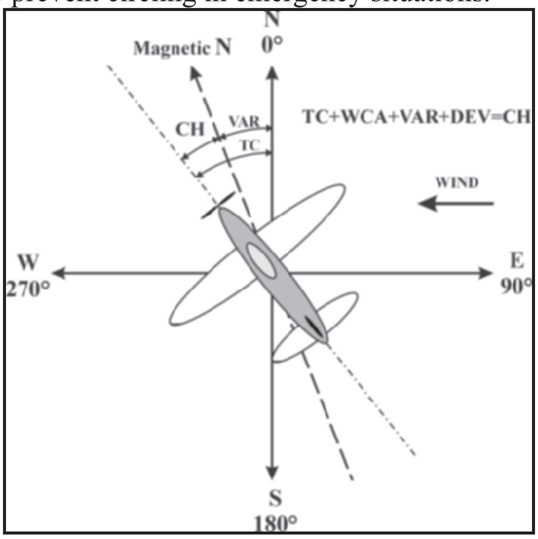

Figure 68. The wind correction angle.

Gliders and light motor aircraft must be equipped with a radio as well as the basic navigation instruments before being registered[16]. Basic instruments are: airspeed indicators, altimeters and magnetic compasses. The simple magnetic compass on an airplane operates the same way as one on a ship (Figure 64). It has a circular scale on which is fixed a permanent magnetic bar. The direction indicator floats in liquid (liquid magnetic compass) (Figure 69). The gimballed magnetic compass is fixed to its base by joint connections. Such magnetic compasses are incomparably more accurate and less sensitive to changes of flight direction than magnetic compasses with a simple construction, although they are much more expensive.

5. Conclusion

The oldest and easiest way to set a course is to use a magnetic compass. Compass measurements are easily made and reliable. Compasses are unsuitable for navigation in the four following cases:

1. If the frame is magnetic and has too much influence on the magnetic compass.
2. If natural or artificial objects have an unpredictable influence on the Earth's local magnetic field.
3. If the local vertical component of the Earth's magnetic field is larger than the horizontal component.
4. If it is impossible to take reliable measurements with a magnetic compass because the frame is accelerating too fast.

Figure 69. Liquid magnetic compass on a light aircraft.

The modern electronics industry enables the construction of digital magnetic compasses which are precise and inexpensive devices for setting courses. They are also accurate in most cases where traditional magnetic compasses are not reliable. Electronic magnetic compasses were introduced for aeronautical navigation during the Second World War. In the 1970's microprocessors were included in electronic magnetic compasses. Such digital magnetic compasses are able to measure a local Earth magnetic field with high accuracy and reliability[17]. These compasses have an electric output signal and, therefore, are easily handled. They can also display data in multiple locations simultaneously And can be used in a closed control loop, where they can be automatically controlled, even if the precise course with reference to the magnetic North Pole is unknown[18].

A normal magnetic field strength in Slovenia[19] is somewhat greater than 47,000 nT and changes is no more than 100 nT (1 nano-Tesla = 10^{-9} T) in a full day. Measuring the change in field strength is important for aeronautical and shipping navigation. Such measurements also enable predictions of changes connected with the Sun's activity, which affect the space around the Earth: its weather, density of the atmosphere, influence of solar wind on electric power-lines and transformers, and changes in Earth satellite orbits[20].

Digital observatories IMO (INTERMAGNET Magnetic Observatories) must be equipped with a magnetometer for measuring the three-components of the Earth's magnetic field and with a scalar magnetometer for measuring the absolute value of the Earth's magnetic field. Such instruments should take measurements each second with a resolution better than 1 nT. The measurement results should first be registered and then processed each minute and during the following minute sent to a GIN (Geomagnetic Information Node). In Europe this information is sent via METEOSAT, the geostationary satellite for observing the Earth, or via Internet[21].

Two of the six GIN world centres for collecting geo-magnetic measurements are in Europe and operate in near real time. More than 80 geo-magnetic observatories through out the world are connected to INTERMAGNET (International Real-time Magnetic Observatory Network) via these centres. INTERMAGNET has been active since 1991 and makes it possible to collect and store measurements of changes in the Earth's magnetic field. The collected data are communicated to all IMO's and are available to other users as well.

In order to join the International Project INTERMAGNET, the Republic of Slovenia would have to find an appropriate place to construct a digital geomagnetic observatory with low magnetic pollution and a low Earth magnetism gradient (< 1nT/m). The location must not have any direct electric currents such as those associated with electric railways and industries with electroenergetic sources. Finally, a location for a magnetic observatory must be guaranteed to stay magnetically clean in the future. These conditions can only be ensured by an appropriate national institution with expert staff supported by the governmental administration.

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DISCUSSION

Question (Ivan Butchvarov): What is the difference between the magnetic and gyrotheodolite in use?

Answer (Rudi Cop): When a theodolite is oriented by magnetic compass, the magnetic variation and deviation must also be taken into consideration when carrying out measurements regarding true North. Magnetic variation changes with time and by changing the location. Magnetic deviation is caused by the influence of the frame of a magnetic compass on the accuracy of the measuring instrument.

A gyrocompass enables direct theodolite orientation regarding true North. Its operation does not rely on the Earth's magnetism.

In both cases, when using navigation instruments for defining a position, it is necessary to take into consideration the accuracy of the measuring instrument.

Question (Angelo de Santis): Your presentation focuses our attention on an important matter: even if the geomagnetic community can give information to airports / heliports about the mean value of declination, this value can change rapidly and significantly during magnetic storms that can last for a few days. This is something to be clearly said to operators of aircraft. A possible solution is to ask these operators to look at websites when magnetic recordings from observatories or space weather forecasts are shown (see, for example, the ingv website: www.ingv.it).

Answer (Rudi Cop): Small changes in the Earth's magnetic field over smaller or greater areas do not only influence the accuracy of the navigation instruments but, as the measurements taken in Slovenia and elsewhere in the world have proved, there is also a mutual connection between the state of the magnetic field and the reactions of living beings in it. There is considerable work in this field to be done by researchers, among other things, to determine the ability of the crew to operate the aircraft in the case of short term changes in the Earth's magnetic field caused by the solar wind.