The Geomagnetic Field: an Actively Changing Global Phenomenon

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ABSTRACT

The Earth's magnetic field varies on a wide range of timescales, from long time trends caused by internal processes to rapid fluctuations caused primarily by solar events. Nowadays, the magnetic field is continually being monitored by worldwide networks of observatories. Different indices have been developed to characterise the magnetic activity, and various services exist to alert users in case of a magnetic disturbance.

SAMENVATTING

Het aardmagnetisch veld varieert op uiteenlopende tijdschalen. Processen binnenin de aarde zijn verantwoordelijk voor lange-termijn trends terwijl snelle fluctuaties veroorzaakt worden door zonneactiviteit. Vandaag de dag wordt het magnetisch veld permanent gemonitord door een wereldwijd netwerk van waarnemingsstations. Verschillende indices zijn ontwikkeld om de activiteit van het magneetveld te karakteriseren, evenals diensten om gebruikers te waarschuwen in geval van een verstoring van het magneetveld.

RÉSUMÉ

Le champ magnétique terrestre varie sur une grande variété d'échelles temporelles: des tendances à long temps causées par des processus internes, jusqu'aux fluctuations rapides causées principalement par des événements solaires. Aujourd'hui, le champ magnétique est continuellement surveillé par des réseaux mondiaux d'observatoires. Différents indices sont développés pour caractériser l'activité magnétique, et divers services existent pour alerter les utilisateurs en cas d'une perturbation magnétique.

Introduction

Magnetic fields are not perceptible to humans, so it took several steps for mankind to make an article like this a possibility: first magnetometers had to be designed as an extension to our senses. This happened with the Chinese invention of the compass, more than 1000 years ago, based on the naturally magnetized lodestone rock. Second, magnetometers had to be deployed over the totality of the Earth so that the morphology of the geomagnetic field could be revealed. It was so that in 1600, William Gilbert published De Magnete, based upon his extensive collection of magnetic measurements from around the globe, which showed that the Earth itself is like a giant magnet. Carl Friedrich Gauss set up the "Magnetischer Verein" from 1836 to 1841 to measure the magnetic dipole field of our planet by combining measurements taken in up to 50 observatories disseminated on Earth. He then also showed that 5 % of the measured field came from outside the Earth.

The geomagnetic field proved to be very useful for navigators, as its horizontal component pointed towards North even when all other bearings were lost. It is so that the magnetic compass was widely introduced on ships. However, there were errors: slight constant deviations from North were often detected in several places over the Earth and the deviations exhibited slow secular changes as first seen by Henry Gellibrand in 1635. From time to time, the pointing direction would vary rapidly over time as was noticed in 1724 by George Graham. Those "errors" are the very base of the research going on in geomagnetism: slow deviations and variations are the result of the geomagnetic field set-up mechanism inside the Earth's core while rapid variations are externally induced, mainly by solar events that propagate through the solar wind and the magnetosphere to exert their influence.

The geomagnetic field

The simplified Earth can be seen as being made of layers. Going down from the surface we identify the layers of relevance here: lithosphere, mantle, outer core, inner core. The geomagnetic field morphology is like that of a dipole field currently inclined at around 11 degrees to the Earth's rotation axis. However, a magnet cannot exist in the thousands of degrees heat inside the Earth. This field is generated instead in the outer core by dynamo action in which the iron-rich fluid convects as a result of the heat sources contained within it. This fluid convection, occurring across the existing magnetic field lines and in the presence of the Earth's rotation, induces electrical currents that generate further magnetic fields. The power required to generate the geomagnetic field is estimated at about 10^{13} W. Although no definitive explanation for the geomagnetic field powering has been given as yet, the energy sources are thought to come from a combination of cooling of the Earth's core giving a freezing of the outer core's iron and a growth of the solid inner core.

The core field is the dominant component of the Earth's surface and near surface field being of the order 90 % of the field strength. Whatever variations we observe at the surface has been low pass filtered by the mantle. The core field proper changes on timescales of months to millennia and includes reversals: the polarity (North or South) of the magnetic poles reverses. Reversals occur on average every 200.000 to 500.000 years and last probably a few thousand years. The lithospheric field is stable, except on geological timescales, and is the consequence of the presence of rocks rich in magnetic minerals. Lithospheric fields contribute up to 5 % of the measured field near the surface, but can be very large near localised crustal magnetic anomalies. At the Earth's surface it is apparent that the Earth's internal magnetic field is complex. The most recent model is a spherical harmonic expansion of order 14 with 224 coefficients. All of these coefficients vary with time so it is necessary to continuously monitor the field both at the surface and in space to update models. Some current models of this secular variation use expansions of degree 18. In order to correctly quantify the 3D geomagnetic vector, each measurement must sample three independent vector components. The three most frequently used axis systems for describing it are (see Fig. 1):

Cartesian: X (North component), Y (East component), Z (vertical component, positive downward).
Cylindrical: D (magnetic declination angle, positive East), H (horizontal component), Z
Spherical: D, I (magnetic inclination angle, positive downward), F (magnetic field induction intensity).

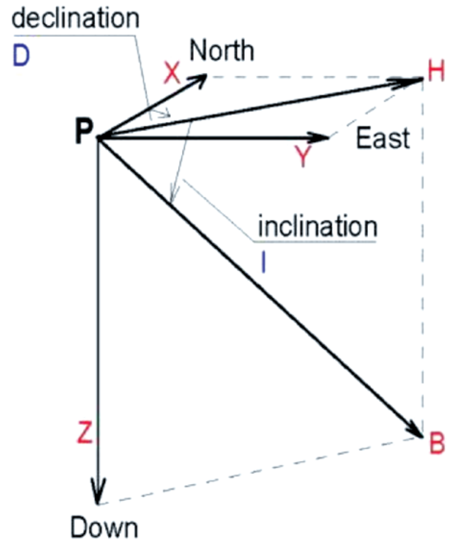

Fig. 1: The geomagnetic field components

Fig. 2: The magnetic observatory in Dourbes, Belgium

Observation of the geomagnetic field

Geomagnetic observatories

A good magnetic observatory is a place where precise, continuous long-term measurements of the geomagnetic field are made and from where definitive data are regularly published to the wider scientific community. Hence, the first task is to monitor the natural geomagnetic field for a long time (at least one year) by continuously measuring the 3D geomagnetic vector. We are dealing with a very wide-frequency spectrum of signals, whose characteristic times extend from centuries to subseconds. It is therefore important to take care of long-term instrument stability and reliability, standardization, continuity in data formats and fast sampling capability.

Only the natural geomagnetic field is to be measured, so the observatory installation should be completely nonmagnetic: it should not affect the direction or amplitude of the geomagnetic vector in a measurable way. For good measurements, the observatory should respect special conditions: low magnetic gradient and identity of field changes in the vicinity of the observatory. Actually, the observatory site is an integral part of the observatory instrumentation; hence the quality of measurement depends on the magnetic hygiene of the surroundings and the buildings, on low magnetic noise conditions, as well as on the stability of the pillars bearing the directional orientation sensors. Detailed, and still up-to-date, information about observatories can be found in Jankowski and Sucksdorff (1996).

Belgium has two magnetic observatories: in Dourbes (Fig. 2) and in Manhay. They are part of the INTERMAGNET network (www.intermagnet.org). A third Belgian observatory is under construction in the Princess Elisabeth Base in East-Antarctica.

Nowadays, the geomagnetic field is also measured by Earth orbiting satellites and it is expected to have them permanently aloft in the future. Since their measurements are taken on moving platforms and that they often cross the electrical currents circling our globe, satellites nicely complement the measurements taken on the ground in the observatories.

How to measure the geomagnetic field

A magnetometer is mainly categorized by it sensing element. For carrying out measurements according to its tasks in an observatory environment, the sensing techniques have reached a good level of maturity and are now mainly represented by the fluxgate and the proton magnetometers. Since a 3D vector is monitored, one can either measure the modulus and orientation angles of the vector or measure induction components in a Cartesian coordinate frame. Angles of orientation and frames should be referenced to the true North and to the Nadir. Component magnetometers will measure projections of the geomagnetic vector with large constant parts, like X and Z, while orientation magnetometers will be sensitive to the orientation of the field with respect to the sensor and measure small projections like D or Y. Component and orientation magnetometers are not yet capable of continuously measuring all the field components with the required absolute accuracy. Therefore, an observatory measurement setup uses a combination of instruments: a variometer to measure the variation of the field components about baseline values in a continuous and unattended way at the required sampling rate, say 1 Hz, and absolute measurements performed regularly, say two per week, by an observer with the adequate instrumentation (DI-flux, proton magnetometer) to establish the values of the baselines. Further information on measurement methods and equipment can be found in Rasson (2007) and Turner et al. (2007).

Global monitoring and data centers

As Gilbert, Weber and Gauss experienced, monitoring the geomagnetic field globally is a challenge. Nowadays, a network of magnetic observatories exists and endeavors to cover evenly the entire globe. This is not easy, considering the uneven land coverage and the very unevenly available resources assigned to this task by the different countries. So if one looks at Fig. 4, it appears that there is a North-South bias in addition to the notable lack of observatories in the oceans. Magnetic satellites are contributing greatly in improving the coverage and the recently launched SWARM mission will provide precise mapping of the field.

INTERMAGNET (International Real-time Magnetic Observatory Network) was created in order to establish a worldwide network of cooperating digital magnetic observatories. Those observatories agree to adopt modern standard specifications for measuring and recording equipment and to exchange data in close to real time. Moreover, INTERMAGNET extends technical support for maintaining and upgrading existing magnetic observatories as well as for establishing new ones. INTERMAGNET data consists of time series of the geomagnetic vector, sampled at the round minute and carefully filtered to avoid aliasing effects. This data, collected at the Intermagnet Magnetic Observatories (IMOs) represented on Fig. 4, is continuously available from the Geomagnetic Information Nodes (GINs) within 72 hours. The data come in different accuracies: reported (as recorded in near real time), adjusted (corrected for artificial spikes and jumps), and definitive (reduced to baseline so that it has absolute accuracy). The latter is made available a few months after the end of each year at the earliest and surely with the production of the yearly DVD. People needing real-time data use the reported or adjusted data, available from the GINs in daily ASCII files. Access to the recent definitive data is through the website (www.intermagnet.org); older data is available on the website or the DVDs. Definitive data comes in monthly files in binary code. Browsers are available for easy perusal and inspection. The data is freely available for bona fide scientific users. If any commercial aspects are involved, the user should seek a financial arrangement with the IMO directly.

Another development is the introduction of data sampling at 1 Hz, which is in demand from the space weather community. In 2013, INTERMAGNET defined an internal data file format (based on netCDF) for interchange of this type of data. In the next years, it is anticipated that 1 Hz data will progressively become the norm in IMOs and that GINs will start disseminating and archiving them.

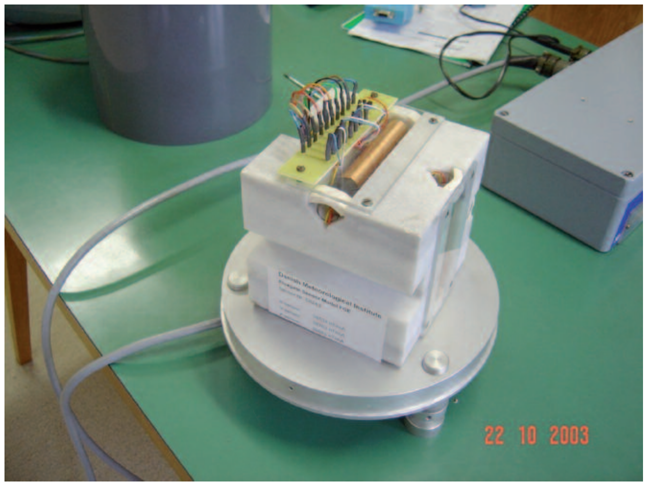

Fig. 3: A triaxial variometer using fluxgate sensors. The fluxgate uses the nonlinear field-induction relationship of a saturable ferromagnetic core. The core, usually a rod or a ring, is subjected to both the DC field to be measured, and an auxiliary artificial AC field. This offset sinusoidal excitation will create a distorted AC signal in a pick-up coil around the core. Hence the detection of its even harmonics provides a DC signal proportional to the DC field to be measured.

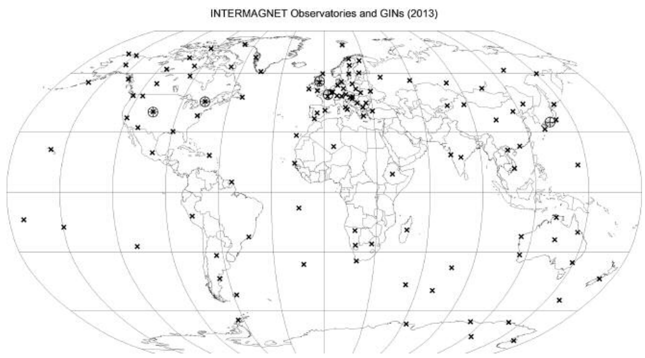

Fig. 4: Worldwide network of geomagnetic observatories being part of the INTERMAGNET network

Activity indices

The main purpose of the geomagnetic activity indices is to quantify the degree of the geomagnetic field disturbance (local or global) and to characterise the origin and time scale of the field variations. There is a large number of indices but they can be sorted into two major types – one, indices that estimate the global energy input in the magnetosphere, which is the purpose of the “planetary” indices (e.g., the so-called K-indices, such as K_p, K_m, a_p and A_p) and two, indices that separate and quantify the variations representative of a localised/isolated effect (e.g., the auroral electrojet index, AE, and the storm-time index, Dst, for the ring current variations).

The K index accounts for the morphological characteristics of the transient irregular variations of the field and it is designed to characterise the geomagnetic activity during a 3-hour interval at a certain location. The K index is derived from the amplitude of the variations of the field's horizontal components (the H and D pair, or alternatively, the X and Y components) after subtracting the daily solar regular (SR) variation for the particular component. The K index is an integer number between 0 (indicating 'very quiet' geomagnetic field) and 9 ('very disturbed' geomagnetic field), corresponding to the larger of the two ranges measured in the field's horizontal components over the specified 3-hour period. In fact, the K index is a code, and although expressed in integers, it refers to a level ("class") on a quasi-logarithmic scale consisting of 10 gradually increasing ranges. The same 3-hour intervals of the universal time day (UT) (00–03, 03–06, 06–09, 09–12, 12–15, 15–18, 18–21, 21–24) are used at any station where K indices are produced (Fig. 4). These intervals are long enough to correctly account for certain perturbations of one or two hours in duration (e.g. bays) and, at the same time, are short enough not to affect too much of the daily index when such short-term disturbances happen to occur over two consecutive intervals (Menvielle et al., 1995).

To estimate the global field variations, a derivative mean standardized K index, a "planetary" K index (K_p) is defined, based on the ranges of variation within the 3-hour periods observed in the records from several selected geomagnetic observatories – currently 13 – located at sub-auroral latitudes, between about 45° and 65° magnetic latitude (see Fig. 5). After weighting and averaging of the local K indices, the standardised mean K_p value for every 3 hours of the day is obtained again on the same quasi-logarithmic scale but in addition to the original 10 integers, additional intermediate values containing one and two thirds of a K unit (KU) are introduced by use of symbols '+' and '-', thus having 28 K_p values in total: 0, 1 –, 1, 1 +, 2 –, 2, 2 +, 3 –, … , 7 +, 8 –, 8, 8 +, 9 –, 9. The K_m index is calculated in the same manner as K_p but based on a larger set of measurements – from 20 observatories, half of which in the Northern hemisphere and the other half in the Southern hemisphere.

The 3-hourly equivalent range (a_p) index is derived from the K_p index by conversion back to field components variations and is expressed in units of 2 nT. Thus, for example, an a_p value of 18 is equivalent to a 36 nT perturbation. The A_p index is the daily average of a_p, expressed also in units of 2 nT, and provides a maximum disturbance measure useful to identify major geomagnetic storms chronologically (by date and start time) and by amplitude from largest to smallest.

The Auroral Electrojet (AE) index is designed (Davis and Sugiura, 1966) to provide a quantitative measure of the auroral zone magnetic activity produced by enhanced ionospheric currents flowing below and within the auroral oval. AE is the total range of deviation at an instant of time from quiet day values of the horizontal magnetic field (H) around the auroral oval (see Fig. 5). The advantages of AE are that it can be derived on an instantaneous basis or from averages of variations computed over any selected interval. Second, it is also a quantitative index which, in general, is directly related to the processes producing the observed magnetic variations. Third, its method of derivation is relatively simple, digital, and objective and is well suited to present computer processing techniques. Finally, it may be used to study either individual events or statistical aggregates. The AE disadvantages are: first, the distribution of the observatories in operation is not uniform along the auroral zone and second, a loss of only one station could lead to omission of significant disturbance events. AE has been usefully employed, both qualitatively and quantitatively, as a correlative index in studies of substorm morphology, the behavior of communication satellites, radio propagation, radio scintillation, and the coupling between the interplanetary magnetic field and the earth's magnetosphere.

Fig: 5 Global map with the locations of the observatories which measurements are used for the derivation of the AE (blue), Kp (green), and Dst (red) indices.

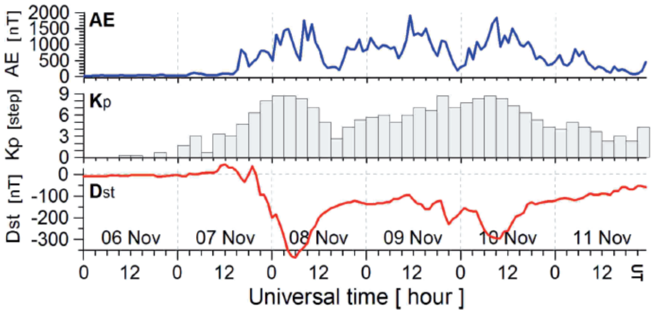

Fig: 6 Variations of the AE (top), K_p (middle), and Dst (bottom) indices during the geomagnetic storm period of 07–11 November 2004.

The storm-time index, Dst, gives the average (in longitude) depression of the horizontal component in low (geomagnetic) latitudes due to the ring current, which is proportional to the total kinetic energy of the particles injected and trapped in the Van Allen (electron) belt. The Dst index, which is regarded as a function of storm time, represents the axially symmetric disturbance magnetic field at the dipole equator on the Earth's surface (cf. Fig. 5). Major disturbances in Dst are negative, namely decreases in the geomagnetic field. These field decreases are produced mainly by the equatorial current system in the magnetosphere, usually referred to as the ring current. The neutral sheet current flowing across the magnetospheric tail makes a small contribution to the field decreases near the Earth. Positive variations in *Dst* are mostly caused by the compression of the magnetosphere from solar wind pressure increases. *Dst* is derived continuously as a function of *UT* and its variation will clearly indicate the occurrence of a magnetic storm – start, intensity, and duration (Fig. 6). *Dst* can be derived on an instantaneous basis.

Services: K-Logic

A nowcast system (K-LOGIC) for real-time processing of geomagnetic field measurements, estimation of the local geomagnetic index *K*, and dissemination of the results has been developed. The K-LOGIC system has a complex, modular design aimed at timely data acquisition, fast production and distribution of the index value, while allowing for easy installation of further software developments. Key modules are the system control – including timing, quality control (QC), and communication – data acquisition (linked to IMF, the Instruments and Measurements Facility), database management, data processing (input screening/cleaning, actual *K* index calculation, post-processing), reference matrices, communication display and dissemination (Stankov et al., 2011).

This is a time-controlled system (rather than an event-driven system) producing a regular output (the K index value, data quality/processing evaluation, alerts) with certain fixed time resolution, currently set to sixty minutes. Theoretically, the time resolution can be increased up to one minute, since that is the time resolution of the used measurements; however, such high resolution is not needed at the moment because user applications demanding such rate are not yet identified.

The data used for this service comes primarily from observations carried out at the geomagnetic observatory in Dourbes, Belgium. Variations in the field vector components and modulus are routinely digitally recorded. Observations are distributed via INTERMAGNET. One minute vector magnetic field data (*H*, *D*, and *Z* components) is used as obtained directly from the instruments, i.e. untreated, meaning that gaps and spikes are present in the input data set. The precision is 1 s for time, and 0.1 nT for the field components. An example of the evolution of the different components of the field during quiet as well as disturbed days can be seen in Fig. 7.

Given the pre-determined time resolution of the nowcast, the data acquisition module updates the data buffer with the measurements available since the last run. After that, the data pre-processing starts. This involves the identification of data gaps and spurious values, providing information for quality control and update of the buffer with cleaned data. The main task of the data processing module is to compute the ranges (max–min) of the horizontal components, then select the largest one, and produce the *K* index value from this. All phases of the data processing are monitored closely by the quality control system in order to immediately assess the quality of the data input and processing. An example of the hourly *K* values during a seven day period can be seen in the top panel of Fig. 7. The local *K*-

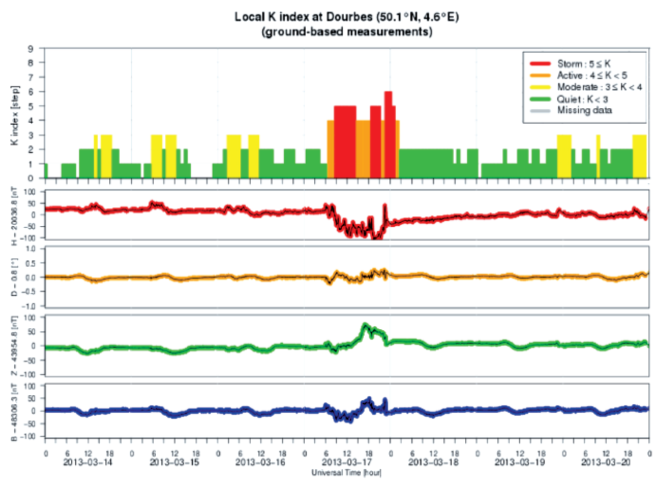

Fig. 7: Magnetic activity index (top panel) and field components (*H* in red, *D* in orange, *Z* in green and *B* in blue) in Dourbes during the geomagnetic storm of March 17, 2013.

index is available in real time on the website www.ionosphere.meteo.be.

If the *K* value exceeds the threshold for a geomagnetic storm (*K* = 5) – and the dataset used for calculating *K* is of sufficiently high quality – an alert is generated and sent to the user. The alerts are some of the higher-level products generated by the system. Other products envisaged are the definitive *K* index (based on the linear elimination method) and various statistical analyses that may be requested by the user. These tasks are to be performed in the post-processing unit. Finally, it should be noted that all interaction with the user is done not directly but via the Communication Display and Dissemination facility. In this way, the system is more flexible to respond adequately to the particular user needs.

Conclusion

The international scientific community aims at developing reliable services for nowcasting and forecasting the space weather effects on the present-day technological systems (e.g. on the electrical power systems, aviation, applications based on the Global Navigation Satellite Systems) and key components in these efforts are the reliable geomagnetic field measurements and the nowcast and forecast of the geomagnetic activity. Also, a great variety of scientific models rely on the geomagnetic indices as input parameters.

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