A comprehensive view of the Earth's magnetic field from ground and space observations

Mioara Mandea, Hermann Lühr, Monika Korte, Georgios Balasis, Hans-Joachim Linthe, Kumar Hemant, Eberhard Pulz, Patricia Ritter, Martin Rother, Claudia Stolle, Erwan Thébault, Ingo Wardinski

Seit einigen Jahren gewinnen eine Reihe von Satelliten Beobachtungsdaten des Erdmagnetfelds in hoher Qualität. Das GeoForschungsZentrum Potsdam ist zum einen aktiv an dieser Art von Satellitenmissionen beteiligt und unterhält zum anderen eine wachsende Anzahl geomagnetischer Observatorien am Boden. Wir beschreiben hier die unterschiedlichen Charakteristika von Observatoriums- und Satellitendaten hinsichtlich Qualität, räumlicher Abdeckung und zeitlicher Verteilung. Es werden Beispiele präsentiert, wie aus der Kombination von an der Erdoberfläche gewonnenen Daten und Satellitenmessungen deutlich verbesserte Beschreibungen des Erdmagnetfelds gewonnen werden können. Damit eröffnen sich neue Möglichkeiten für Studien der Flüssigkeitsbewegung im Erdkern, der Leitfähigkeit des Erdmantels, der Zusammensetzung der Lithosphäre bis hin zur Dynamik von Stromsystemen in Ionosphäre und Magnetosphäre.

In recent years, high-quality observations have been obtained from a number of geomagnetic satellites. GeoForschungsZentrum Potsdam (GFZ) is actively involved in these kinds of satellite missions, but is also involved in maintaining and extending ground-based geomagnetic field measurements using a number of observatories. We discuss the different characteristics of observatory and satellite data, like quality, spatial coverage and temporal distribution. Examples are presented about how the combination of ground-based data and satellite measurements can provide improved descriptions of the geomagnetic field, and how they offer new opportunities for studies ranging from core flow, mantle conductivity and lithospheric composition to the dynamics of ionospheric and magnetospheric currents.

Introduction

The Earth's magnetic field is mainly due to a geodynamo mechanism in the liquid, metallic outer core. The *lithospheric* contribution, due to rocks which acquired information about the magnetic field at the time of their solidification from the molten state, adds to the dominant core magnetic field. In addition, external fields represent a third contribution which is produced primarily by the interaction of the solar wind with the magnetosphere, and their intensities vary with the solar wind speed and the orientation of the embedded magnetic field. The solar wind modifies current systems in the magnetosphere and ionosphere surrounding the Earth, producing magnetic variations on varying time scales from a second to a solar cycle. Moreover, these highly variable external fields cause secondary, induced fields in oceans and electrically conductive regions of the lithosphere and the upper mantle.

To fully describe the geomagnetic field it is necessary to either measure the intensity 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. The unit used to describe the geomagnetic field is the nanoTesla (nT), with the Tesla in fact being the unit for magnetic flux density.

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, as discussed above and varying in magnitude. These are:

1) the core field, generated in the fluid outer core, which ranges between 30000 nT at the equator to 65000 nT at the poles;
2) the lithospheric field, generated by magnetized rocks, generally having a strength of the order of tens to a few hundreds of nT, but reaching a few thousand nT over strong anomalies;
3) the external fields, generated by magnetospheric and ionospheric currents, and varying from fractions of a nT up to a few thousand nT during large magnetic storms;
4) the electromagnetically induced field, generated by currents induced in the crust and the upper mantle by the time-varying external field, amounting up to some tens of nT.

Separating these contributions directly is impossible (Mandea and Purucker, 2005). In 1838 Gauss using spherical harmonic functions developed a method to describe the geomagnetic field globally, providing a rough separation between internal and external contributions to the field. Geomagnetic field models based on spherical harmonics are still widely used, but due to the multitude of sources, a strict separation of all contributions is not feasible.

The geomagnetic field is also subject to temporal variations over a broad range of time scales, including complete reversals of the whole field on geological times. The so-called short-term variations are detectable over time scales spanning fractions of a second to decades. The very short period variations (seconds to hours) can safely be attributed to sources external to the Earth, while the longer-period variations (annual to decades) are due to both solar cycle variations with its harmonics and core field variation (known as *secular variation*). These different variations are superimposed and while it was previously thought that their main part is of external origin, recently the question of the shortest time scales of the core field observable at the Earth's surface has again become controversial.

Systematic observations of the geomagnetic field exist for almost two hundred years, providing information about its morphology and time-evolution. An example with one of the longest data series worldwide is the Adolf Schmidt Geomagnetic Observatory of GFZ Potsdam at Niemegk. Time variations, as shown in Fig. 1, are revealed by continuous magnetic records, monitored by geomagnetic observatories where the permanent installation of instruments ensures reliable measurements of the geomagnetic field. Additionally, so-called magnetic repeat-station measurements are regularly made at particular locations and distinct times to resolve the secular variation in specific areas as well as to increase the density of available ground-based magnetic data distribution. In addition, new satellite measurements, being made continuously since 1999, are greatly improving our knowledge of the geomagnetic field all over the globe. GFZ contributes to these with its CHAMP satellite, which is in operation since July 2000 and is expected to continue until 2008. The GFZ Potsdam is unique in combining the expertise of measuring the geomagnetic field from both ground and space, to investigate a broad range of internal and external field variations. Here, we give a tour of the different kinds of measurements, with special emphasis on how ground and satellite measurements complement each other. More detailed scientific results on specific problems about the geomagnetic field are described in the part concerning Section 2.3 activities of this report.

Measuring the Earth's Magnetic Field

Magnetic observatories

Historically, the role of magnetic observatories was to monitor the secular change of the geomagnetic field, and this remains one of their most important tasks. Some

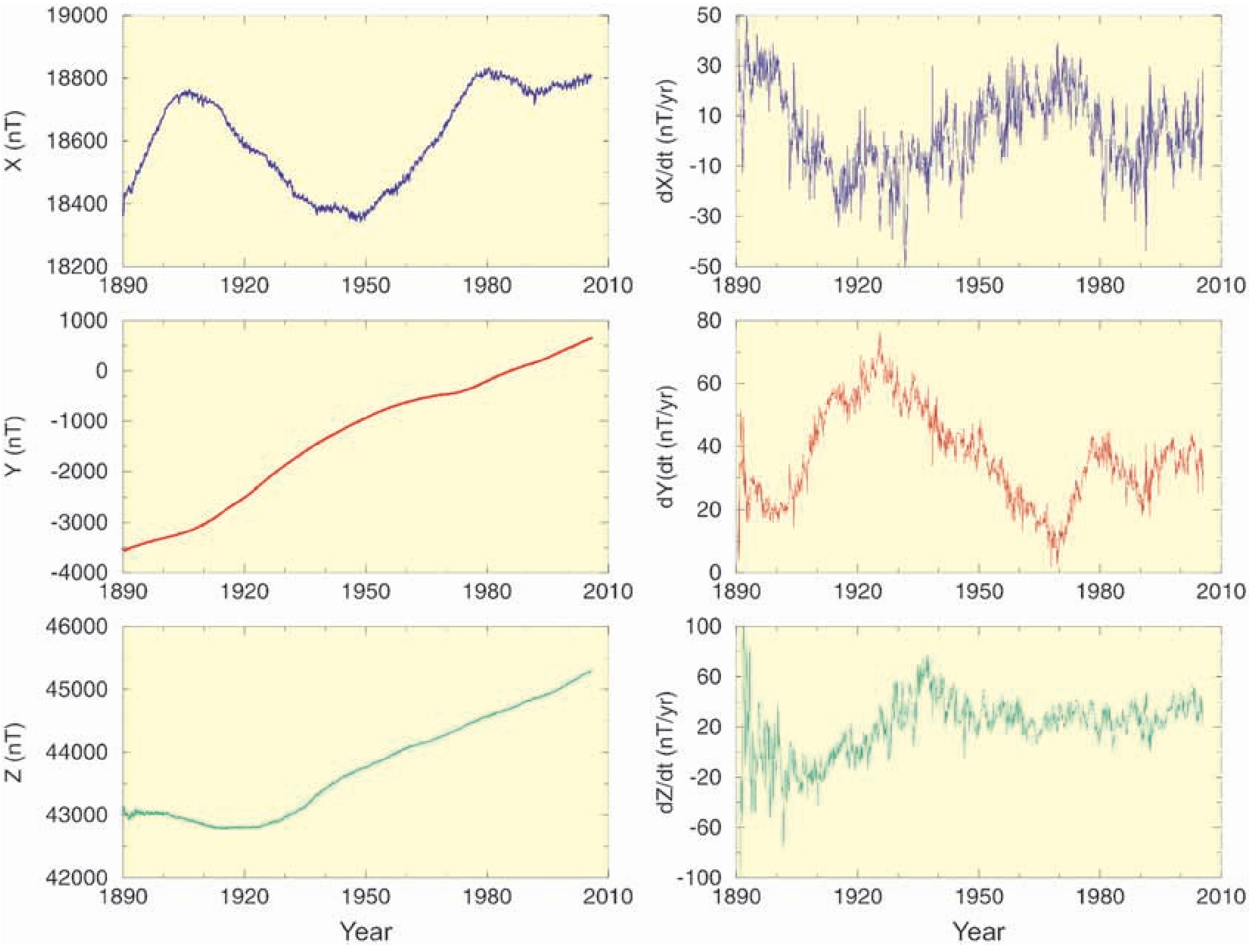

Fig. 1: *Monthly mean values of the geomagnetic field (left) and its secular variation (right) recorded at the Niemegk observatory (since 1930) and its predecessors at Seddin (1906-1930) and Potsdam (1890-1906). The three components are in the directions of geographic north (X), east (Y) and vertically down (Z).*
Monatsmittelwerte des Erdmagnetfelds (links) und ihre Säkularvariation (rechts), gemessen am Observatorium Niemegk (seit 1930) und den Vorgängerstationen in Seddin (1906-1930) und Potsdam (1890-1906). Die drei Komponenten zeigen in Richtung geographisch Nord (X), Ost (Y) und vertikal nach unten (Z).

***Fig. 2:** Participants of the international colloquium celebrating the 75th anniversary of the Adolf Schmidt Geomagnetic Observatory Niemegk of GFZ Potsdam.*
Teilnehmer des internationalen Festkolloquiums aus An-lass des 75-jährigen Bestehens des Adolf-Schmidt-Observatoriums für Geomagnetismus des GeoForschungsZentrums Potsdam in Niemegk. (Fotos: R. Holme, E. Pulz, GFZ, und H.-D. Scherz)

observatories were installed at the end of 19^{th} century. One of them was the Potsdam Magnetic Oservatory, which started regular operation on January 1, 1890. Today, the old building on Telegrafenberg hosts the Paleomagnetic Laboratory, maintained by Section 3.3 of GFZ Potsdam. Due to anthropogenic disturbances of the measurements, caused mainly by the electrified railway system, the observatory had to be moved to Seddin in 1906, some 20 km southwest of Potsdam. It operated there for only 20 years, until it had to be moved again for similar reasons. On July 30, 1930 a new observatory was opened in Niemegk. The Adolf Schmidt Geomagnetic Observatory, run by GFZ since 1992, celebrated its 75^{th} anniversary in 2005, bringing together geomagnetists from around the world for a celebratory colloquium (Fig. 2). Today, more than 200 observatories are in operation worldwide, but not all of them satisfy the technical standard to participate in the INTERMAGNET project, requiring a guaranteed level of data quality and near real-time data exchange (Fig. 3). To run a modern magnetic observatory generally involves continuous *variation measurements* of three field components (one-minute or even one-second data sampling) which are recorded automatically by fluxgate magnetometers. However, these instruments are subject to drifts arising from sources both within the instrument (e.g. temperature effects) and the stability of the instrument mounting. Moreover, due to the large difference in amplitude between the very strong, but only slowly varying core field and the much weaker but fast external variations, the latter can be determined with much higher accuracy if constant values are compensated for and only the variations are measured about a baseline. These measurements do not provide absolute values and the instruments are known as variometers. *Absolute measurements* of the full vector field, sufficient in number to control the instrumental drift, are necessary to calibrate the variometer recordings.

A scalar measurement of the field intensity, obtained commonly by a proton magnetometer, is considered as absolute: it depends only on our knowledge of a physical constant (gyromagnetic ratio) and a measurement of fre-

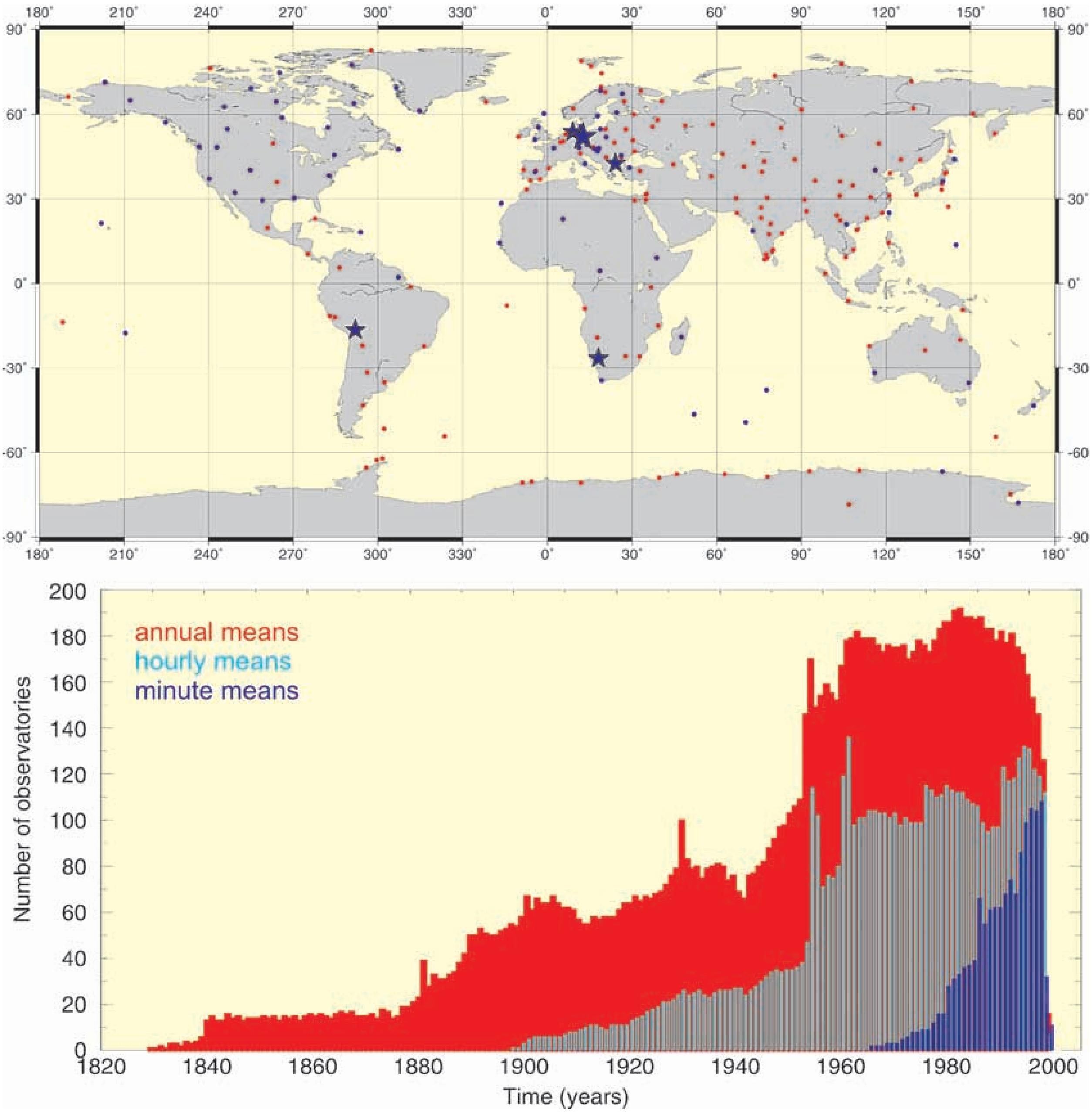

***Fig. 3:** Global distribution of geomagnetic observatories (top) and amount of available observatory data (bottom). Only those marked in blue fulfill the INTERMAGNET quality standard with near real-time distribution of minute data. Some of the observatories marked in red only provide annual mean data. The distribution is highly non-uniform, with the northern hemisphere better covered than the southern hemisphere. The blue stars mark Niemegk observatory of GFZ and the stations currently run in cooperation with local institutions.*
Weltweite Verteilung geomagnetischer Observatorien (oben) und deren verfügbare Daten (unten), Stand 2000. Nur die blau markieren Observatorien erfüllen den INTERMAGNET-Standard mit Verfügbarkeit von Minutenwerten in quasi Echtzeit. Einige der rot markierten Stationen liefern nur Jahresmittelwerte. Die Verteilung ist sehr ungleichmäßig, mit deutlich besserer Abdeckung der Nordhalbkugel. Die blauen Sterne markieren das Observatorium Niemegk des GeoForschungsZentrums und die Observatorien, die zurzeit in Kooperation mit lokalen Instituten betrieben werden.

quency, and it can be achieved with great accuracy. However, scalar magnetometers determine only the strength of the magnetic field and provide no information about its direction. Absolute measurements of the direction of the geomagnetic field, i.e. the angles of declination and inclination, are performed with an instrument known as a fluxgate-theodolite (DI-flux) that requires manual operation and takes about 30 minutes per measurement. In a land-based observatory, such absolute measurements are typically made once to twice a week and are used to monitor the drift of the fluxgate variometers. So far no instrument exists to carry out the complete absolute measurements automatically. In an attempt to change this, the Niemegk observatory together with the Technical University of Braunschweig is currently developing an alternative instrument to carry out automatically the absolute three-component measurements of the magnetic field to calibrate variometer recordings (Fig. 4).

Fig. 4: *Orienting a first prototype of an instrument under development at Niemegk observatory. This instrument eventually will allow for the automatic absolute determination of three field components.*
Der erste Prototyp eines am Observatorium Niemegk in Entwicklung befindlichen Messgeräts, das hier ausgerichtet wird. Dieses Gerät wird nach Fertigstellung die automatische Absolutmessung von drei Magnetfeldkomponenten ermöglichen. (Foto: E. Pulz, GFZ)

Modern land-based magnetic observatories all use similar instrumentation to produce similar data products. The fundamental measurements recorded are one-minute values of the vector components and scalar intensity. The one-mi-nute data are important for studying variations in the geomagnetic field external to the Earth, in particular, the daily variation and magnetic storms. Data from 13 observatories distributed worldwide are used to produce the Kp global magnetic activity index. This index is the most commonly used parameter to characterise the level of magnetic disturbances. It is currently computed and distributed around the world by Niemegk observatory. Other indices of special or regional variations are derived from different subsets of observatory data. From the standard one-minute data, hourly, daily, monthly and annual mean values are produced. The monthly and annual mean values are useful to determine the secular variation originating in the Earth's core. The quality of secular-variation estimates depends critically upon the long-term stability, i.e. the quality of the absolute measurements at each observatory. However, as mentioned earlier, not all existing magnetic observatories have the technical standard to achieve the desired data quality, and the global network of stations has large spatial gaps. GFZ Potsdam is increasing its efforts to improve the global data coverage by supporting observatories worldwide and installing new observatories in cooperation with local institutions. Our involvement currently includes, besides Niemegk, the existing observories Wingst (Northern Germany) and Panagjurishte (Bulgaria), and the newly installed ones at Villa Remidios (Bolivia) and Keetmanshoop (Namibia), see Fig. 3.

Magnetic field satellites

Since the 1960s, the Earth's magnetic field intensity has been measured intermittently by satellites. Only recently have there been a few missions dedicated to measuring the full vector field, using star cameras to establish precisely the direction of a triaxial fluxgate sensor in space. High-quality fluxgate sensors onboard spacecraft are instruments with a very high temporal resolution, but they suffer from small drifts of the order of some nT/yr. For a multi-year mission this requires absolute intensity measurements onboard satellites in order to calibrate the vector instrument (as well as for ground observatories). This is achieved by combining the measurements from all the different orientations a satellite aquires of the ambient magnetic field over a day. It is possible to perform a full in-orbit calibration of the fluxgate instrument at regular intervals (e.g. Olsen et al.,

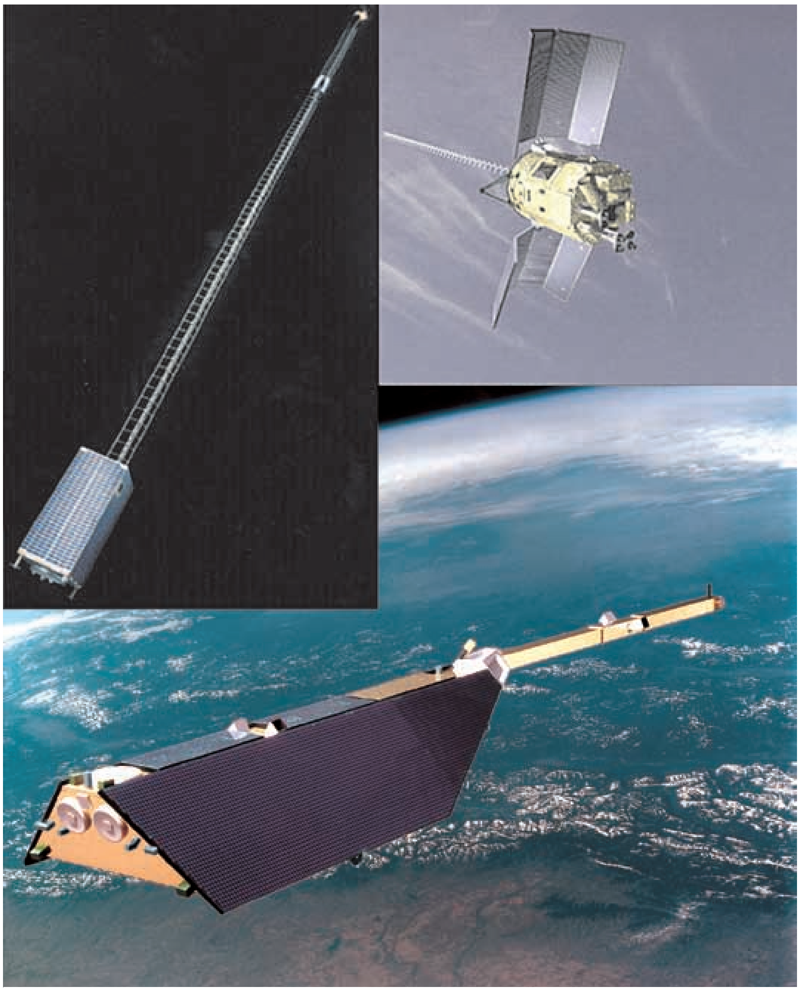

Fig. 5: *The three satellites currently measuring the geomagnetic field from space: CHAMP (bottom), Ørsted (upper left) and SAC-C (upper right).*
Die drei Satelliten, die gegenwärtig das Erdmagnetfeld vektoriell aus dem Weltraum vermessen: CHAMP (unten), Ørsted (oben links) und SAC-C (oben rechts).

2003). Special attention has to be paid to the magnetic disturbances coming from the satellite. In order not to degrade the measurements both magnetic field instruments are kept remote from the spacecraft body by mounting them at the end of a few meter long non-magnetic boom (Fig. 5).

The first satellite mission that provided valuable vector data for geomagnetic field modeling was MAGSAT (Langel et al., 1980), which resulted in magnetic measurements over a six month period between 1979 and 1980. The following 20 years were without high-quality satellite magnetic field missions. The first satellite to improve the situation was Ørsted, launched in 1999, and still partially operational after 7 years. The satellite carries as its primary scientific instruments a tri-axial fluxgate magnetometer and a star camera for measuring the vector components of the geomagnetic field. Its position along the orbit is determined by using Global Positioning System (GPS) receivers. The satellite's main body carries the electronics while an 8-meter boom hosts the magnetic field instruments. It takes the Ørsted satellite about 100 minutes to orbit the Earth in its near-polar orbit. The local time of the orbit plane changes by 0.9 minutes per day, and the data are from an altitude range of 640 to 850 km. The same fluxgate and star camera package together with a scalar magnetometer were mounted on the SAC-C spacecraft, launched about two years after Ørsted. SAC-C has a circular orbit at an altitude of 702 km, and a fixed local time (LT), crossing the equator at 10:24 and 22:24 LT. This experiment has suffered from a malfunctioning star camera which has prevented the acquisition of any vector data.

From development to operation, CHAMP (Challenging Minisatellite Payload) is a GFZ project. Launched in July 2000 with its highly precise, multi-functional and complementary payload elements (magnetometer, accelerometer, star sensors, GPS receiver, laser retro reflector, ion-drift meter) and its orbital characteristics (near polar, low altitude, long duration), CHAMP has generated simultaneously highly-precise gravity and magnetic field measurements for more than 5 years. CHAMP has a length of 8.33 m (including the boom) and an initial mass of 522 kg. With an orbital period of 93 minutes, and an initial altitude of 454 km, the satellite moves rapidly through local time, with a change of 5.45 minutes/day. Attitude stability relies on magneto-torquers and a cold-gas propulsion system. Its aerodynamic shape together with tri-axial attitude control ensures that a stable flight configuration is achieved in the relatively dense atmosphere at low-altitude. The two redundant magnetic fluxgate sensors are mounted together with the star cameras on an optical bench providing a mechanical stability between these systems of better than 20 arcsec. The optical bench is located about 2 meters away from the spacecraft's main body, and the Overhauser Magnetometer is mounted at the tip of the 4-meter boom. This configuration is a compromise between avoidance of magnetic interference from the spacecraft and cross-talk between the vector and scalar magnetometers. The almost circular and near-polar (87.3 deg. inclination) orbit allows for a homogeneous and almost complete global coverage of the Earth by gravity and magnetic field measurements.

Magnetic data

Three parameters are important when dealing with magnetic data: quality, spatial distribution, and temporal coverage.

Data Quality

Many magnetic observatories have operated for decades, some for more than 100 years. Up until the 1990s many observatories were still operating in the classical mode, with analogue recording and, consequently, requiring long periods for data processing and dissemination, as well as providing less accurate final data. Developments in technology since that time have allowed more and more observatories to change to digital recordings, while at the same time updated equipment has seen data quality gradually improve from 10 second sampling at 1 nT resolution to the current INTERMAGNET standard of 1 second sampling at 0.1 nT resolution. Data recorded in observatories in real time are known as *variational or preliminary data*, as they lack the absolute calibration and may have a baseline offset, which itself can have a slow drift. These preliminary data are useful for investigations concerned with relatively rapid changes in the magnetic field occurring over time periods of less than a couple of days, i.e. the external field contributions. However, for studies involving longer time scales and in particular, changes of the core field, absolute data time series are essential. These *definitive data* are obtained through data processing, with adjustments made for baseline drift based on the regularly performed absolute measurements at each observatory. These steps for obtaining definitive magnetic data are necessary to satisfy the minimum requirements of an INTERMAGNET Magnetic Observatory (IMO): long-term stability of the order of 5 nT/year and an accuracy of ±10nT for 95 % of reported data and ± 5nT for the definitive data.

With the launch of three satellites (Ørsted, CHAMP and SAC-C) since 1999, high-accuracy scalar and vector magnetic measurements have now become available from near-Earth orbits. The Ørsted Overhauser proton-precession magnetometer measures the scalar values of the magnetic field with an accuracy of < 1nT, while the fluxgate magnetometer together with the star camera provides vector data with a precision of < 3-5 nT. The same package is mounted on the SAC-C spacecraft, but the vector data cannot be used, as the star camera has given no information during the course of the mission, possibly because of a cabling problem on the boom. As a consequence, magnetic-field measurements from SAC-C are restricted to the 1 Hz values from the scalar magnetometer, with an accuracy of better than 4 nT. This higher value is partially due to the uncertainty of the spacecraft fields.

Currently, the best available magnetic satellite data are those produced by the CHAMP mission. The CHAMP scalar magnetometer provides an absolute in-flight calibra-

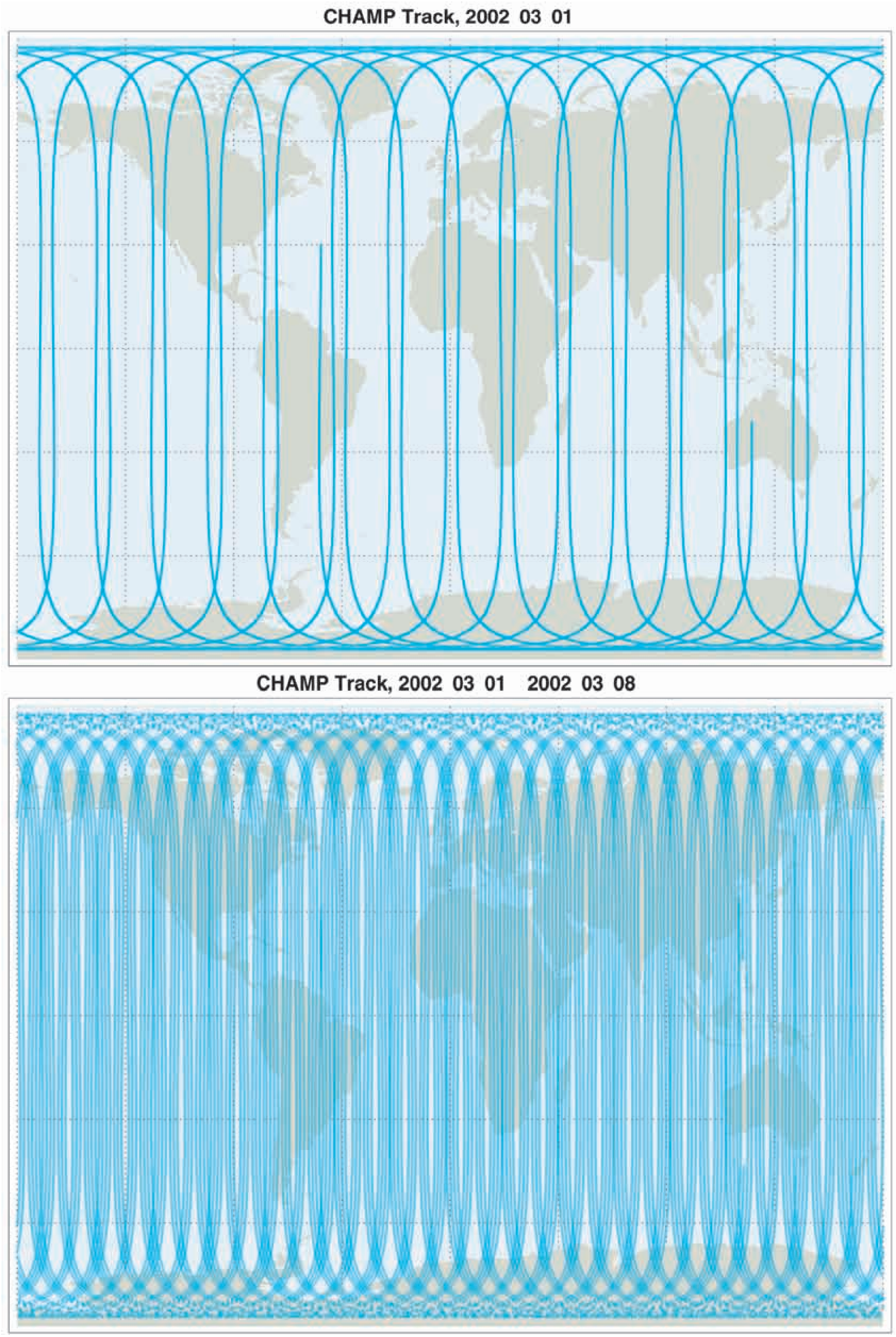

Fig. 6: Coverage of the Earth with CHAMP satellite magnetic data after one day (top) and one week (bottom).
Abdeckung der Erdoberfläche durch magnetische Daten des CHAMP-Satelliten nach einem Tag (oben) und einer Woche (unten).

tion capability for the vector magnetic field measurements. A dedicated program ensuring the magnetic cleanliness of the spacecraft allows for an absolute accuracy of < 0.5 nT for the magnitude data. For the fluxgate magnetometers, the overall noise level is of the order of 50 pT. The scalar calibration using the absolute Overhauser observations is run on a daily basis, and the instrument parameters for the fluxgate data processing are updated every two weeks. The corrections applied to the data concern the scaling factors, field offsets, non-orthogonality and the stray fields from the satellite. A remaining uncertainty of the vector data is due to thermal bending of the optical bench. These bending angles have to be determined in special modelling procedures. Data from both the vector fluxgate magnetometer and the scalar Overhauser magnetometer are available to the worldwide community through the data center, ISDC, at GFZ.

Spatial distribution

The distribution of magnetic observatories over the globe (see Fig. 3) is highly non-uniform, with the northern hemisphere having better coverage than the southern hemisphere. The observatory distribution is a key parameter in determining the secular variation on the global scale. This is the reason why in some regions, for example the Pacific, the uncertainty in the secular variation is of the order of hundreds of nT/yr (Mandea and Macmillan, 2000), while in better-covered regions such as Europe, it is a few nT/yr. One possibility to counterbalance this uneven geographical distribution is the use of an adequate weighting scheme (Langlais and Mandea, 2000). However, adequate weighting cannot make up for the lack of information in the regions sparsely covered by data. The only definitive way to remedy this issue is to establish additional observatories, in particular, in the southern hemisphere and to upgrade all existing observatories to the INTERMAGNET standard.

Another possibility to improve our knowledge of the secular variation is to have well-distributed global measurements from satellites. The data provided by each of the three satellites currently in orbit ensure a good coverage of the Earth's surface in a very short period of time. Fig. 6 shows the orbit tracks for one day and for one week, respectively, for the CHAMP satellite. The coverage over one week already appears sufficient for a good data distribution. However, these plots are based on all available measurements, without considering data quality and selection criteria with respect to external disturbances. For core field and secular variation studies a selection of quiet time data is necessary as long as we do not understand all individual field sources in sufficient detail to separate them. This can lead to a drastic reduction in the amount of usable data.

Temporal coverage

Since the installation of the first magnetic observatory in 1832 by Gauss, their number has continuously increased. However, the number of observatories providing hourly means or one-minute data (INTERMAGNET observatories) is lower than the total number. Some observatories only offer annual means as they do not have the modern equipment to produce high-resolution data (Fig. 3).

The time span covered by satellite missions is quite short in comparison to observatory time series of the order of decades to more than a century. The first satellite providing magnetic vector data was MAGSAT in 1980, which was in operation for only 6 months. Since 1999/2000, there are three satellites providing high accuracy magnetic vector data. However, there is an important difference between observatory and satellite data: observatories provide continuous time series from one location, whereas a satellite records the field values while travelling through space. The data series thus contain both spatial and temporal variations, and the purely temporal resolution for a given location is worse than that of an observatory (at best 1 sample/day).

Joint analysis of observatory and satellite data

The launch of the Danish satellite Ørsted marked the start of the international initiative *Decade of Geopotential Field Research* declared by the IUGG, which highlighted the importance of gravity and magnetic field measurements from space. The GFZ satellite CHAMP was launched shortly after Ørsted. Once more, we want to stress that there are important differences between observatory and satellite data. The separation of spatial and temporal signals is a challenging task for satellite data alone. Moreover, the ground-based and satellite data are taken at different distances to the various sources. Using the Ørsted and CHAMP measurements together with magnetic observatory data yields maximum information. Only the combination of satellite and ground-based data will improve our knowledge of the individual sources of the geomagnetic field enough to allow a highly accurate separation of sources over multi-year time intervals. However, considerable difficulties exist in carrying out joint analyses of ground-based and satellite data due to their different spatial and temporal information content. In the following, a few examples of different ways to take advantage of the combination of these measurements are given.

Core field and secular variation

IGRF models

The best-known global geomagnetic field model is the International Geomagnetic Reference Field (IGRF). A new model in this series is produced every 5 years, from a range of measurements provided by magnetic observatories, ships, aircraft and satellites. Several candidate models, including one from the GFZ geomagnetism group (Maus *et al.*, 2005), are submitted each time to a dedicated working group of the International Association of Geomagnetism and Aeronomy (IAGA), which determines a final reference model. This model series, based on a classical spherical harmonic analysis of a vast amount of data, represents the magnetic field generated in the Earth's core. Even in the present era of the GPS navigation system, the

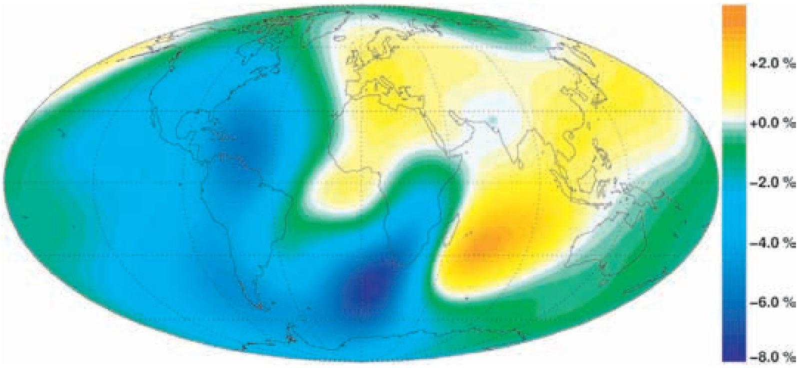

Fig. 7: *Percentage change of the geomagnetic field intensity from 1980 to 2001, as determined by the MAGSAT and CHAMP satellites*
Änderung der Intensität des Magnetfelds von 1980 bis 2001 in Prozent, hergeleitet aus den Messergebnissen der Satelliten MAGSAT und CHAMP

IGRF models and particularly their description of declination still play an important role for navigation purposes. Magnetic compasses are used as backup systems on ships and aircraft, so the declination has to be known at all locations and times. IGRF declination information is even implemented in the GPS system for orientation support. The IGRF models also play an important role as a standard to eliminate the core field contributions in aeromagnetic surveys for geological studies or prospecting. The quality of models in this series has dramatically increased over the last two field generations. Indeed, since the 8th generation (Mandea and Macmillan, 2000), the main-field models are currently defined up to spherical harmonic degree/order 13 (compared to degree 10 for all previous generations). The recent models (9th and 10th generation) represent the fruitful combination of satellite and observatory data. The satellite data on the one hand are needed to ensure a good distribution over the globe, while on the other, information about magnetically quiet conditions are provided by the observatories. Moreover, the continuous observatory data improve the secular variation estimates in the models. The use of both satellite and ground-based data has dramatically improved the quality of geomagnetic field models (Olsen et al., 2006).

Secular variation models

Modelling the secular variation on characteristic timescales of the order of a few decades can be significantly improved if we take advantage of all the available magnetic satellite data. We can compare the core field descriptions obtained from the Ørsted and CHAMP missions over the last few years to those from the MAGSAT mission of 1979-1980 (Hulot *et al.*, 2000). It is obvious that the magnetic field does not change uniformly over the Earth (Fig. 7). While the overall strength of the dipole field is decreasing, there exist a few regions where the field strength is increasing. An extremly strong decrease is seen in two areas, in the South Atlantic and in the Meso-American region.

More detailed information can be derived from a time-dependent model of the secular variation between 1980 and 2000, such as the one developed by Wardinski (2005). The endpoints of this time interval were chosen because of the availability of high-quality field models derived from satellite measurements during these epochs. Using this a priori field information, the Gaussian coefficients are expanded in time from 1980 until 2000 as a function of cubic B-splines. Between the two endpoints, observatory annual and monthly mean values are used, as well as repeat station data. Satellite and ground-based data complement each other ideally, with the satellite data giving the optimal spatial resolution at both end-points and the ground-based data ensuring optimal temporal resolution in between. The model is used to study the question of shortest observable time-scales of the core field secular variation and to infer from it possible scenarios of fluid flow at the boundary

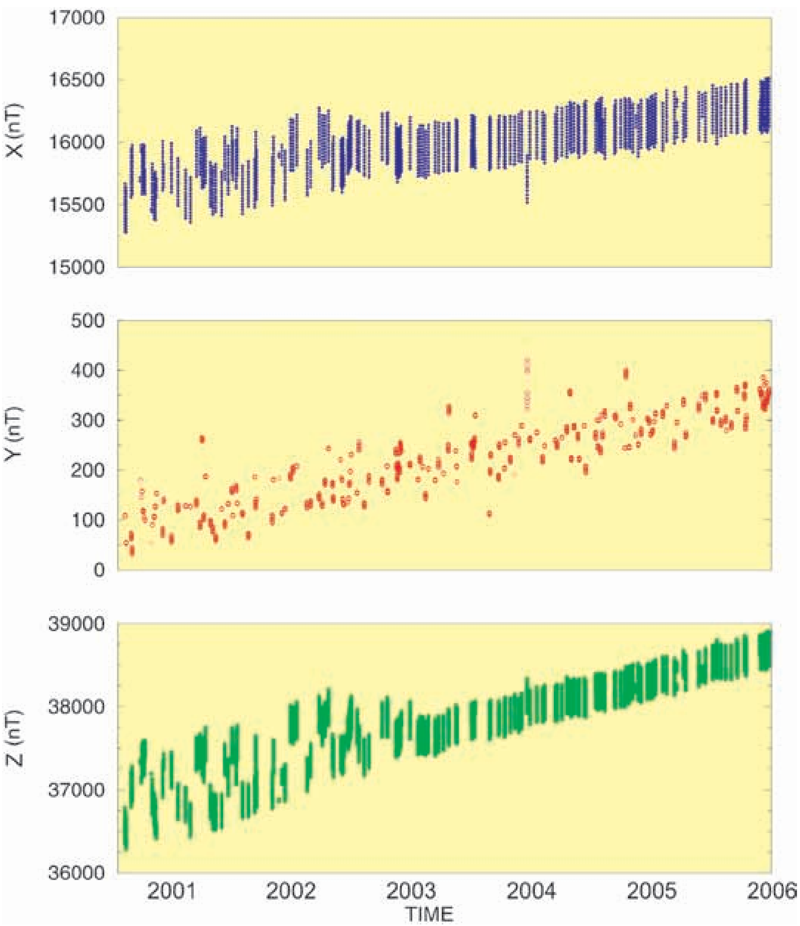

Fig. 8: *All available CHAMP data (X, Y, Z component) in a 1° x 1° longitude and latitude region centered over the Niemegk Observatory.*
Alle verfügbaren CHAMP-Daten (X-, Y- und Z-Komponente) für ein Gebiet von 1° x 1° Länge und Breite über dem Observatorium Niemegk.

between Earth's outer core and mantle in order to gain a better understanding of the geodynamo process. Some more detail on these results is given in the part of Section 2.3 in this report.

Geomagnetic jerks

Over a very short time span, a number of abrupt changes in the secular variation have been noted in the series of magnetic observatories. The cause of these so-called *geomagnetic jerks* is not completely known, but they may reflect the reconfiguration of hydromagnetic motions in the outer core over small scales and short time-intervals. These phenomena are difficult to study, because of their small amplitudes and the overlap of their frequency range with the effect of solar-dependent external variations. Moreover, the highly uneven coverage of the globe by magnetic observatories makes it difficult to study their geometry and evolution, and whether they are of a global nature.

One way to overcome the problem of the uneven spatial distribution of time series is again to turn to satellite data. A good global coverage is obtained from satellite data in a short period of time, but satellite data are not very helpful if our interest is focused on a certain location over a longer period of time. Fig. 8 shows, as an example, all available CHAMP data over an area of 1° x 1° centered on the Niemegk Observatory. It is clear that the temporal resolution, even for a larger area at a fixed position, is not comparable with what observatories provide as continuous data. However, this time series can be used for interpolating the temporal behaviour of the magnetic field. This kind of plot will be a useful first step in studying secular variation, and possibly geomagnetic jerks, at a given position from satellite data.

However, only the joint analysis of observatory and satellite data can really be useful for the global study of geomagnetic jerks. To circumvent the spatial and temporal distribution difficulties, the use of continuous field models derived from ground-based and satellite data, such as the Comprehensive Model by Sabaka et al. (2002, 2004), is one possible solution. Chambodut and Mandea (2005) studied the temporal and spatial distribution of jerks detected in these models over the four last decades. The jerks around 1971, 1980 and 1991 are characterized by a clear bimodal behaviour of their occurrence date. So far, no geomagnetic jerk occured during the lifetime of the magnetic field satellites. A much better description of a jerk could be provided if it were to occur during the time of operation of one or preferably several satellites.

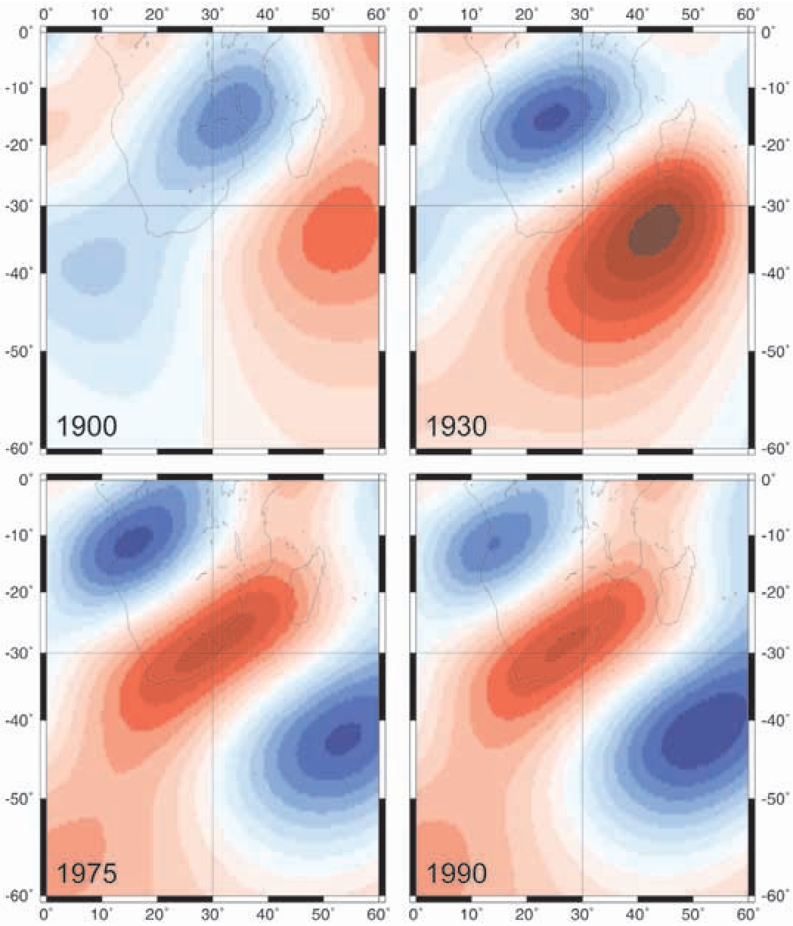

Fig. 9: *Secular variation of the radial magnetic field at the core mantle boundary for epochs 1900, 1930, 1975 and 1990 using the Jackson et al. (2000) model. The extreme values (red/blue) are +/– 13 µT/yr.*
Säkularvariation des radialen Magnetfelds an der Kern-Mantel-Grenze für die Jahre 1900, 1930, 1975 und 1990 nach dem Modell von Jackson et al. (2000). Die Extremwerte (rot/blau) sind +/– 13 µT/a.

South Atlantic Anomaly

Another interesting feature of the core field is the so-called South Atlantic Anomaly. This is a large area of very low field intensity (less than 20000 nT) over South America, the southern Atlantic and southern Africa. Moreover, from MAGSAT and CHAMP data we observed that the field there has been decreasing by some 8 % during the past 20 years (see Fig. 7). Recent studies have identified distinct patches of reversed magnetic flux at the poles and below Africa which could be related to the present day field decrease and might even be a hint that the geodynamo is heading towards a reversal (Hulot *et al.*, 2002). The most prominent feature in this respect is the growing patch of reverse magnetic polarity beneath South Africa. To give an indication of recent changes, Fig. 9 shows the distribution and evolution of the radial magnetic field component at the core-mantle boundary during the past century. The model used here (Jackson *et al.*, 2000) shows a region of reversed field direction (red area) which propagates north-eastward. At present this patch is just below South Africa. Moreover, a large longitudinal difference in field changes is observed, again with a maximum variation in

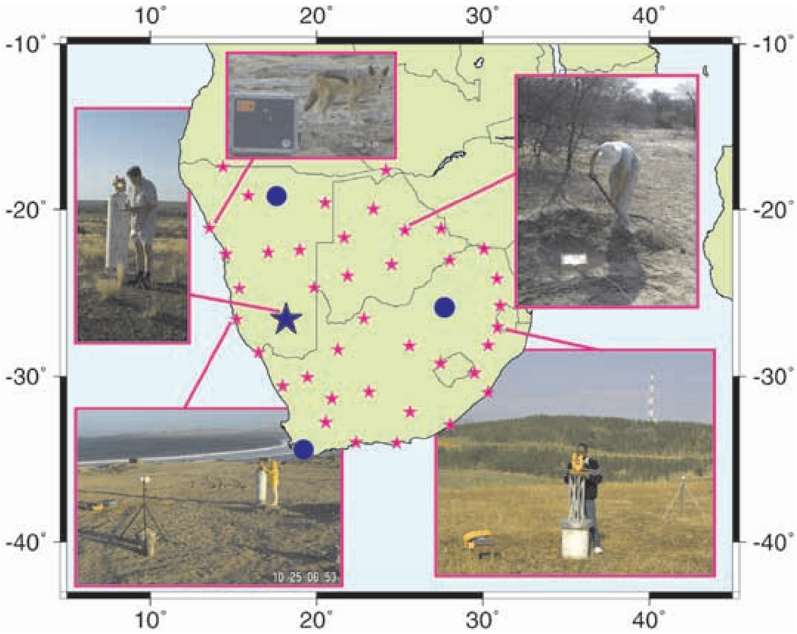

Fig. 10: Two teams from GFZ Potsdam and Hermanus Magnetic Observatory (HMO, South Africa) carrying out magnetic repeat station measurements on the South Africa, Namibia and Botswana networks (red stars). Blue dots are the existing observatories Hermanus, Hartebeesthook and Tsumeb. The star marks the newly constructed observatory Keetmanshoop, a cooperative project between GFZ and HMO.
Zwei Teams von Mitarbeitern des GFZ Potsdam und Hermanus Magnetic Observatory (HMO, Südafrika) führen an Stationen in Südafrika, Namibia und Botswana (rote Sterne) magnetische Säkularpunktmessungen durch. Die blauen Punkte markieren die bestehenden Observatorien Hermanus, Hartebeesthook und Tsumeb, der Stern stellt die Lage des in Kooperation von GFZ und HMO neu errichteten Observatoriums Keetmanshoop dar. (Fotos: M. Mandea und M. Korte, GFZ)

this area. In order to better understand this behaviour, efforts have been started recently to re-establish the southern African repeat station network at a density last surveyed 7 years ago. In a co-operation between Hermanus Magnetic Observatory (South Africa) and GFZ Potsdam, absolute measurements for the three field components and continuous field variations were performed at 40 stations in fall 2005 (Fig. 10). This amount of new data, still in processing at the time of writing, will bring us useful information about the field morphology at the epoch of measurements. To constrain the core field temporal variations further, additional measurements campaigns are planned over the next years.

The orientation of the geomagnetic field in southern Africa is also changing rapidly. In the northwest part of southern Africa the declination is propagating eastward (at Tsumeb) and in the south-east part it is heading westward (at Hermanus and Hartebeesthoek), as shown in Fig. 11. This causes a spatial gradient over the subcontinent which is presently increasing with time. A greater density of continuous observations is required in order to resolve the structure of the field orientation and its evolution. At the end of 2005, again in cooperation with Herma-

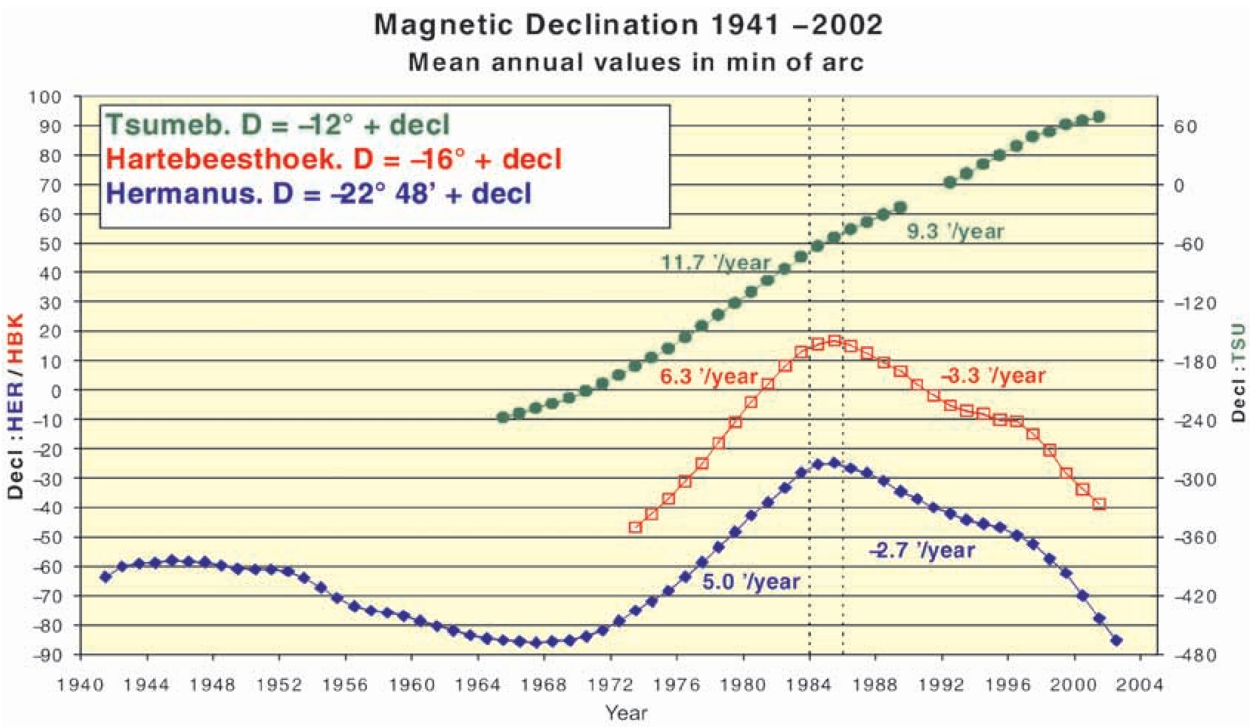

Fig. 11: Evolution of the geomagnetic declination at Hermanus, Hartebeesthook and Tsumeb in the southern African continent.
Änderung der magnetischen Deklination in Hermanus, Hartebeesthook und Tsumeb, alle im südlichen Afrika.

***Fig. 12:** Construction of a measurement hut at the new geomagnetic observatory Keetmanshoop, Namibia.*
Aufbau einer Hütte für magnetische Messungen am neuen Observatorium Keetmanshoop in Namibia. (Foto: H.-J. Linthe, GFZ)

nus Magnetic Observatory, a new magnetic observatory was installed in Keetmanshoop (Namibia), which will provide data from 2006 onward (Fig. 12).

Lithospheric field

Improved lithospheric field models are of great importance for geodynamics studies, but a high spatial data resolution is essential in order to develop them. Satellite data have strongly improved global lithospheric field descriptions (e.g. the MF4 model by Maus et al., 2006), but contain only the large-scale part of the lithospheric field due to the distance of the satellite from the Earth's surface. Aeromagnetic surveys provide detailed pictures of magnetic anomalies, but are generally confined to quite limited regions, thus lacking the large-scale parts of the lithospheric field. Moreover, only field intensity but not the whole vector field information is gained in such surveys. The available ground vector data, on the other hand, are not distributed densely enough to provide sufficient information on the lithospheric field.

It has already been mentioned that the combination of the different data types is not straightforward. However, recently a method for analysing magnetic data from different platforms has been developed and improved by Thébault *et al.* (2004). It is based on the solution of the Laplace equation within a spherical cone, and is referred to as Revised Spherical Cap Harmonic Analysis. It is designed for the inclusion of data from different altitudes, i.e. from ground, aeromagnetic and satellite, for a combined inversion. The method has already successfully been applied for regional modeling. The example shown in Fig. 13 is for Germany. For this area, data from the three German

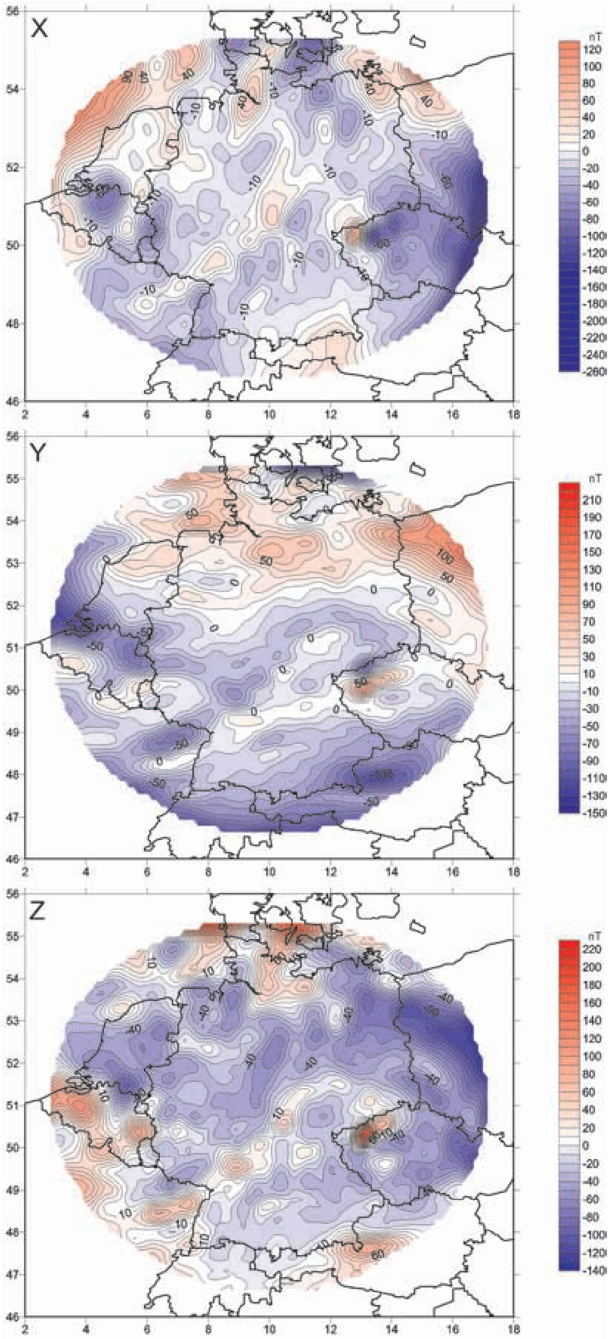

***Fig. 13:** Vector maps of geomagnetic anomalies over Germany obtained by using ground, aeromagnetic and CHAMP satellite data. The north (X), east (Y) and vertical (Z) components of the magnetic field are shown from top to bottom.*
Karten der Magnetfeldanomalien über Deutschland aus der Kombination von Bodendaten, aeromagnetischen Daten und CHAMP-Satellitendaten. Es sind, von oben nach unten, die Nord- (X), Ost- (Y) und Vertikalkomponente (Z) des Magnetfelds dargestellt.

observatories Fürstenfeldbruck, Niemegk and Wingst, German repeat station data, and the available aeromagnetic and CHAMP satellite measurements have been considered. The results are detailed vector maps of the lithospheric geomagnetic field, with the large-scale information coming mainly from the satellite data and the small-scale information mainly from the aeromagnetic, combined with the observatory and in particular the denser repeat station measurements, to give the full vector description.

External field

The development of new analysis techniques for data from satellites and observatories permits an improved separation of the field sources into those which are internal and external to the Earth's surface and also into those above and below the orbits where the satellite observations are made. Thus, in theory, the ionospheric sources which are external to the Earth's surface but below the satellites' orbits, can be isolated. Such a separation allows for better parameterization of both the main geomagnetic field and the external variations which are modulated by solar activity.

In the following example, both satellite and ground-based data is used for studying the ionospheric contribution in magnetic field measurements. The most intense current system in the ionosphere is that of the horizontally flowing auroral electrojet in the auroral oval. The strength and latitudinal position of these current flows depend on many factors, for example on the solar zenith angle, solar wind activity, magnetospheric convection and substorm processes. The characteristics of the auroral electrojet reflect the dynamics and the processes at the magnetopause and in the outer magnetosphere. The electric energy is transported from the magnetosphere to the ionosphere by currents flowing along the field lines. Their intensity controls the electric field and partially the state of ionospheric conductivity, and with it the strength and location of the auroral electrojet (Campbell, 1997). As an example, Fig. 14 shows the horizontal ionospheric current density computed from magnetic field measurements taken onboard the CHAMP satellite (Ritter *et al.*, 2004) and from the IMAGE ground-based magnetometer network (Amm and Viljanen, 1999). For this purpose total field data sampled by the Overhauser Magnetometer on CHAMP and the horizontal magnetic field measurements of the IMAGE network were used. The high correlation shown in Fig. 14 demonstrates the capability of ground-based observations at high latitudes to predict the strength of the electrojet signatures in the satellite magnetic field scalar data.

Conclusion and outlook

The Earth's magnetic field is used for probing the Earth's lithosphere and deep interior and understanding solar-terrestrial relationships; it is also a tool for navigation, directional drilling, geological studies and mineral exploration. The geomagnetic field is shielding our habitat from the direct influences of the solar wind, which becomes apparent during strong geomagnetic storms when the shield is pushed Earth-ward under the influence of the high-speed solar wind. Satellite failures, problems in telecommunication and radio transmission or even regional power failures are often encountered as consequences of them. To map the geomagnetic field and both its spatial and temporal variations, it is essential to improve our understanding of the different processes contributing to it and to increase the predictability of the future field evolution. Data from ground observatories, special surveys over land and sea, and from satellites must be jointly used to achieve these goals.

The data gathered by geomagnetic observatories form the backbone in tracking continuously the magnetic field variations; their data are made available in a variety of time frames ranging from near real-time to 5-year summary information. GFZ is contributing to the worldwide observatory network with its central observatory in Niemegk, from where observatories in Wingst (Northern Germany), Bolivia, Bulgaria and Namibia are operated in cooperation with local institutions. Further cooperations with the aim of bringing more observatories to the INTERMAGNET standard and filling other gaps in the global network are planned.

During the last few years, three new satellites including GFZ's CHAMP were launched by different agencies to measure the Earth's magnetic field from space. Their data are made available by each of the mission data centres. For scientists, the biggest benefit of the high-quality and huge amount of magnetic measurements, from ground and space, is a fresh point of view of the hidden interior of the planet, and its place in the magnetic solar system.

Our magnetic planet will remain under observation with ESA's forthcoming

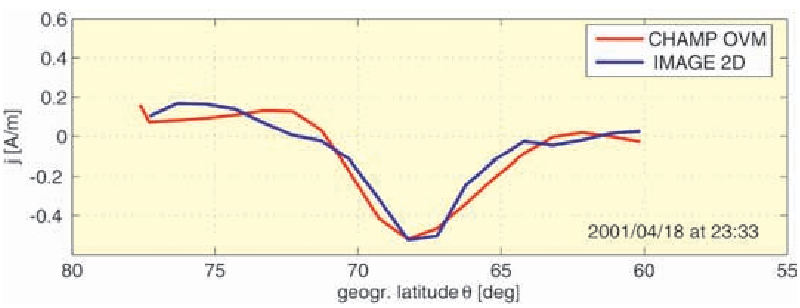

Fig. 14: *The auroral electrojet above Scandinavia obtained from intensity measurements on the CHAMP satellite and horizontal magnetic field measurements by the IMAGE network at the Earth's surface.*
Der polare Elektrojet über Skandinavien, hergeleitet aus Messungen der Magnetfeldintensität des Satelliten CHAMP und Aufzeichnungen der horizontalen Magnetfeldkomponenten an den Stationen des IMAGE-Netzwerks am Erdboden.

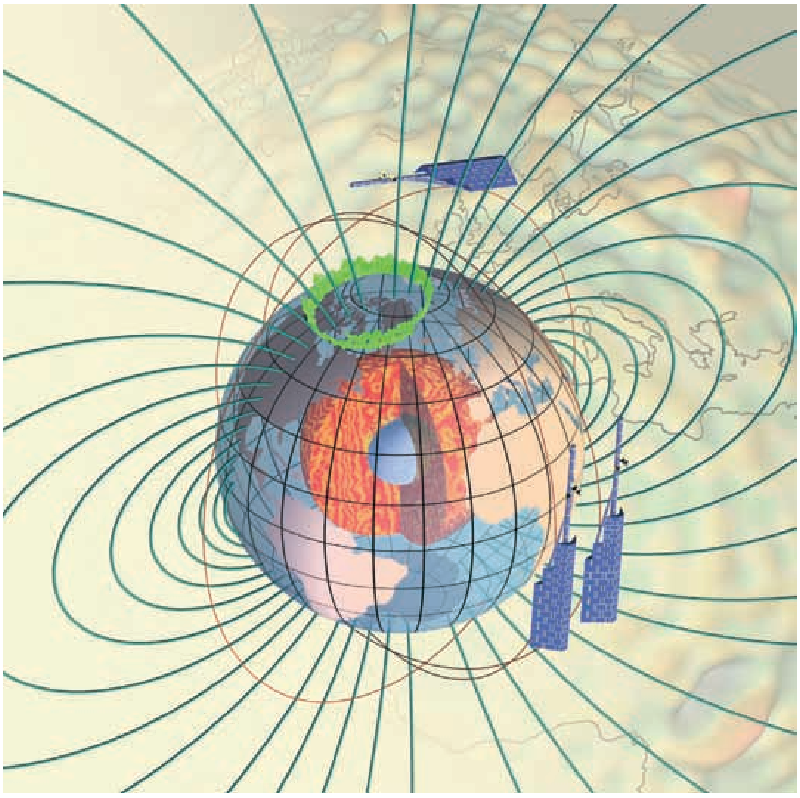

Fig. 15: *Artistic view of the upcoming ESA-mission SWARM that will consist of a three-satellite constellation measuring the geomagnetic field.*
Die kommende ESA-Mission SWARM wird mit einer Konstellation aus drei Satelliten das Erdmagnetfeld vermessen – modellhafte Darstellung.

Swarm mission (Fig. 15). Three satellites will be launched in 2009 and are intended to measure the magnetic field and its variations far more accurately than ever before (Friis-Christensen *et al.*, 2004). Based on the expertise gained from CHAMP, GFZ is well prepared to play a leading role in this ambitious mission.

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All maps were plotted using the GMT software (Wessel and Smith, 1991).

References

Amm, O. and A. Viljanen, Ionospheric disturbance magnetic field continuation from the ground to the ionosphere using spherical elementary current systems, *Earth Planets Space*, **51**, 431-440, 1999.

Campbell, W.H., Introduction to geomagnetic fields, *Cambridge University Press,* 290 pp., 1997.

Chambodut, A. and M. Mandea, Evidence for geomagnetic jerks in comprehensive models, *Earth Planets Space,* **57**, 139-149, 2005.

Friis-Christensen, E., A. De Santis, A. Jackson, G. Hulot, A. Kuvshinov, H. Lühr, M. Mandea, S. Maus, N. Olsen, M. Purucker, M. Rother, T. Sabaka, A. Thomson, S. Vennerstrom, and P. Visser, Swarm. The Earth's Magnetic Field and Environment Explorers, *ESA SP-1279,* **6**, 2004.

Hulot, G., C. Eymin, B. Langlais, M. Mandea, and N. Olsen, Small-scale structure dynamics of the geodynamo inferred from Ørsted and MAGSAT satellite data, *Nature*, 416, 620-623, 2002.

Jackson, A., A. R. T. Jonkers and M. R. Walker, Four centuries of geomagnetic secular variation from historical records, *Phil. Trans. R. Soc. Lond.,* A, 358, 975-990.

Langel, R. A., R. H. Estes, G. D. Mead, E. B. Fabiano, and E. R. Lancaster, Initial geomagnetic field model from Magsat vector data, *Geophys. Res. Lett.,* **7(10)**, doi: 10.1029/0GPRLA000007000010000793000001, issn: 0094-8276, 1980.

Langlais, B. and M. Mandea, An IGRF candidate main geomagnetic field model for epoch 2000 and a secular variation model for 2000-2005, *Earth Planets Space,* **52**pp, 1137-1148, 2000.

Mandea, M. and S. Macmillan, International Geomagnetic Reference Field – the eighth generation, *Earth Planets Space,* **52**, 1119-1124, 2000.

Mandea, M. and M. Purucker, Measurements of the Earth's magnetic field from space, *Surveys in Geophysiscs,* **26**, (No. 4), 415-459, DOI: 10.1007/s10712-005-3857-x, 2005.

Maus, S., S. Maxmillan, T. Chernova, S. Choi, D. Dater, V. Golovkov, V. Lesur, F. Lowes, H. Lühr, W. Mai, S. McLean, N. Olsen, M. Rother, T. Sabaka, A. Thomson und T. Zvereva, The 10th Generation International Geomagnetic Reference Field, *Geophys. J. Int.,* **161**, 561-656, 2005.

Maus, S., M. Rother, K. Hemant, C. Stolle, H. Lühr, A. Kuvshinov, and N. Olsen, Earth's lithospheric magnetic field determined to spherical harmonic degree 90 from CHAMP satellite measurements, *Geophys. J. Int.,* doi: 10.1111/j.1365-246X.2005.02833.x, 2006.

Olsen, N., H. Lühr, T. Sabaka, M. Mandea, M. Rother, L. Toffner-Clausen, S. Choi, CHAOS - A Model of Earth's Magnetic Field derived from CHAMP, Ørsted, and SAC-C magnetic satellite data, *J. Geophys. Int.,* in review, 2006.

Olsen, N., L. Toffner-Clausen, T. J. Sabaka, P. Brauer, J. G. Merayo, J. L. Jorgensen, J.-M. Leger, O. V. Nielsen, F. Primdahl, and T. Risbo, Calibration of the Ørsted vector magnetometer, *Earth Planet Space,* **55**, 11-18, 2003.

Ritter, P., H. Lühr, A. Viljanen, O. Amm, A. Pulkkinen, and I. Sillanpää, Ionospheric currents estimated simultaneously from CHAMP satellite and IMAGE ground-based magnetic field measurements: A statistical study at auroral latitudes, *Ann. Geophys.,* **22**, 417-430, 2004.

Sabaka, T., N. Olsen, and R. A. Langel, A comprehensive model of the quiet-time, near-Earth magnetic field: phase 3, Geophys. J. Int, 151, 32-68, 2002.

Sabaka, T., N. Olsen, and M.E. Purucker, Extending comprehensive models of the Earth's magnetic field with Ørsted and CHAMP data, *Geophys. J. Int.,* **159**, 521-547, 2004.

Thébault, E., J. J. Schott, M. Mandea, and J. P. Hoffbeck, A new proposal for Spherical Cap Harmonic modelling, *Geophys. J. Int.,* **159**, 83-103, 2004.

Wardinski, I., Core Surface Flow Models from Decadal and Subdecadal Secular Variation of the Main Geomagnetic Field, Ph.D., FU Berlin, 132 pp, 2005.

Wessel, P. and W. H. F. Smith, New, improved version of the Generic Mapping Tools released, *EOS Trans. AGU,* **79** 579, 1998.