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New approaches to explore the Earth's magnetic field

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Abstract

New strategies are presented for the analysis of the high-precision geomagnetic data that are currently obtained by the low-orbiting satellites Ørsted, CHAMP and Ørsted-2/SAC-C. The measured magnetic field is the sum of contributions from various sources in the core, crust, ionosphere and magnetosphere, and the accuracy of core and crustal field models is affected by ionospheric and magnetospheric source contributions. A proper parameterization of these external sources, together with a careful data pre-selection, is necessary to avoid spurious effects. In addition, the advantage of having multiple satellite missions measuring simultaneously over different regions of the Earth is discussed, and *swarm*, a proposed constellation consisting of 6 satellites in two different orbit planes, is presented.

1. Introduction

Magnetic fields play an important role in many of the physical processes throughout the universe. In particular, the Earth has a large and complicated magnetic field, the major part of which is produced by a self-sustaining dynamo operating in the fluid outer core. This core field and, in particular, its time changes, known as secular variation, are among the very few means that are available to us for probing the properties of the outer core. The secular variation directly reflects the fluid flow in the outermost core and provides a unique experimental constraint on geodynamo theory.

What we measure at or near the surface of the Earth, however, is the superposition of the core field and fields caused by magnetization of rocks in the Earth's crust, by electric currents flowing in the ionosphere and magnetosphere and by currents induced in the Earth by these time-varying external fields. The separation of these various sources, each of which has its specific characteristics in terms of spatial and temporal variations, is a very challenging task.

For studies of the Earth's core, it is essential that the geomagnetic field models be contaminated as little as possible by fields originating in the Earth's crust or outside the Earth. The separation

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problem is further complicated by the fact that, as seen from a satellite, the magnetic field contribution originating from ionospheric sources at 110 km altitude behaves like an internal field. However, ionospheric and magnetospheric contributions are highly time-variable, and this can be utilized to extract the core- and crustal field.

The improvement in high-precision space instrumentation now enables measurements of the Earth's magnetic field from space with higher accuracy than just a few years ago. However, progress in the exploration of the near-Earth magnetic field not only requires new and improved measurements, but also new methods for data analysis and modeling. Synergetic research beyond the usual division into subdisciplines is necessary in order to utilize this improved data accuracy.

The aim of this paper is to give an overview of present and planned geomagnetic satellite missions, and a discussion about the improvements that these missions will certainly imply regarding the description and our understanding of the Earth's magnetic field. In the first Section we classify the different sources that contribute to Earth's magnetic field according to their temporal behavior, with emphasis on separating signals originating in the Earth's interior and from current systems in the ionosphere and magnetosphere. Present and forthcoming high-precision geomagnetic satellite missions are outlined in Section 2, and measurements from the Ørsted mission are used to demonstrate the now achievable data accuracy. Satellite data are often combined with ground-based data, mostly to obtain a better description of the secular variation. However, ground-based mean values are often contaminated by external current systems and a careful data selection is therefore crucial, as demonstrated in Section 3. In that section we also report on *comprehensive modeling,* a new approach of co-estimating the various sources contributing to the near-Earth magnetic field. Finally, in Section 4 we present *swarm*, a new concept of multi-point, high-precision observations of the near-Earth magnetic field, and we demonstrate the advantage of having multi-point magnetic field measurements.

2. Time-scales of processes that contribute to the geomagnetic field

Various processes contribute to Earth's magnetic field as measured at ground or by low-orbit satellites. These processes can be classified according to their temporal behavior, as shown in Fig. 1.

Although both internal and external sources contribute in principle at all time scales, a common practice in their separation relies on assumptions about their different time behavior. Only the part of the core field that varies on time scales longer than, say, one year is observable at the Earth's surface, shorter fluctuations being heavily attenuated due to the electrical conductivity of the mantle. Hence variations with time scales longer than 4 years are usually attributed to internal field variations (the field due to magnetization in the lithosphere is assumed to be time-independent). Variations with periods shorter than 1 year are attributed to external field contributions.

Such a sharp discrimination is, however, not always possible, and interesting features occur at medium term time-scales where both external and internal sources contribute. The solar-cycle variability of ionospheric and magnetospheric currents produces a clear 11-year geomagnetic variation (cf. Fig. 3), which can be misinterpreted as secular variation of the core field. On the other hand, there are sudden changes in the secular variation, called jerks, which occur within

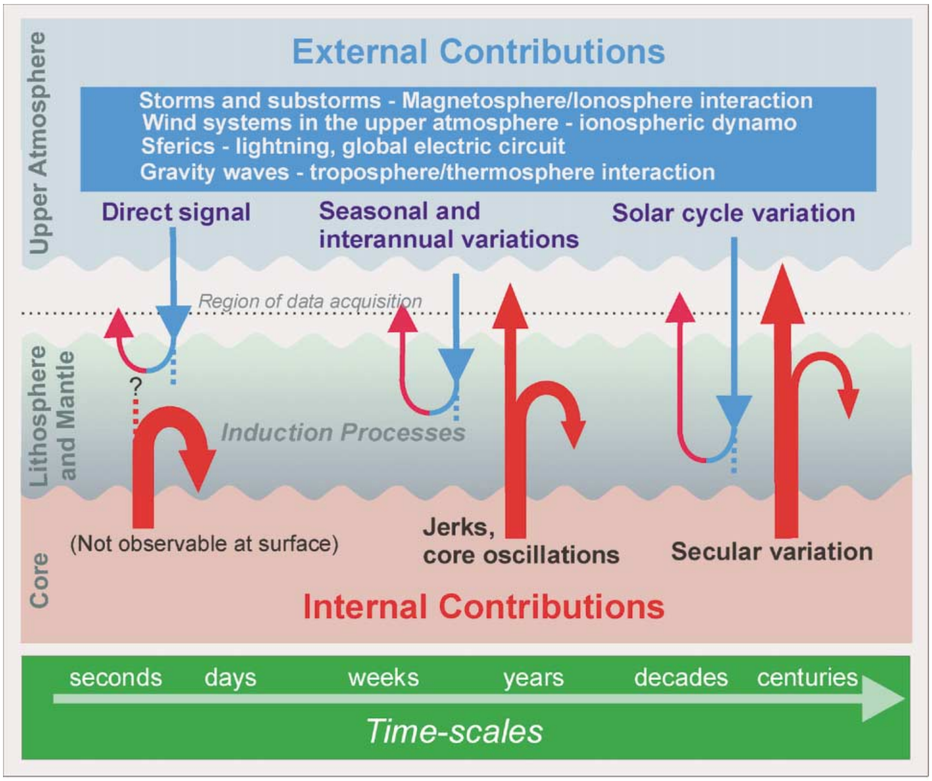

Fig. 1. Classification of the various sources and processes that contribute to the geomagnetic field according to their time-scale.

1–2 years. The spatial characteristics of jerks are still not well known, since no jerk has yet been observed during times where global coverage of data from a satellite was available. Recent studies indicate that jerks may have a recurrence of about 10 years (e.g. De Michelis et al., 1998), which further complicates their separation from the 11-year solar cycle variation of external origin. Oscillations of the Earth's core on time scales of months (e.g. Zatman and Bloxham, 1997) are another hot topic under discussion.

These examples indicate that a firm understanding of internal *and* external sources is required for studying phenomena in the intermediate period range between months and years.

3. High-precision geomagnetic missions during the International Decade of Geopotential Research

The first global high-precision geomagnetic survey was performed with the OGO satellites in 1965–1971. However, these satellites only measured the magnetic field intensity, and models derived from scalar data alone are influenced by the "Backus" or "perpendicular error" effect: Backus (1970) showed that the estimation of models using only scalar data (at fixed altitude) is non-unique. There exist pairs of magnetic field models (i.e. models with different spherical harmonic expansion coefficients) that produce the same magnetic scalar intensity at the considered altitude. This problem led to the decision to fly Magsat, the first mission that measured the vector magnetic field with high precision during the time interval November 1979 to May 1980.

Twenty years after Magsat, a new era in geomagnetic research began with the launch of the Ørsted satellite on 23 February 1999. Ørsted is the first of a series of geomagnetic mapping missions during the *International Decade of Geopotential Research*. CHAMP (launched in July 2000) and the Ørsted-2 experiment on board the SAC-C satellite (launched in November 2000) will continue to deliver high-precision geomagnetic data during the first years of the new millenium (see Table 1). They all carry improved instrumentation compared to Magsat, and in addition they offer the challenging possibility to perform joint analyses of simultaneous measurements from more than one satellite, all of which will certainly enhance our understanding of the Earth's magnetic field and its complex space–time structure.

Table 1
High-precision geomagnetic missions

Satellite		Years	Altitude	Local time
OGO-2,-4 and-6	Scalar	1965–71	400–1,500 km	All local times
Magsat	Scalar and vector	1979–80	350–550 km	06^{00} / 18^{00}
Ørsted	Scalar and vector	1999 –	650–850 km	All local times
CHAMP	Scalar and vector	2000 –	400 km	All local times
Ørsted-2/SAC-C	Scalar (and vector)	2001 –	700 km	10^{30} / 22^{30}

Fig. 2 shows an example of a space-borne high-precision geomagnetic measurement. Moving southward near local midnight and crossing the equator at 12° W, Ørsted sampled the magnetic field along two almost identical passes (less than 1° difference in longitude) on two geomagnetic quiet days (17 and 22 May 1999). The Figure presents the scalar residuals between the measurements and values derived from a spherical harmonic model (up to degree/order $n=13$) of the magnetic field (Olsen et al., 2000).

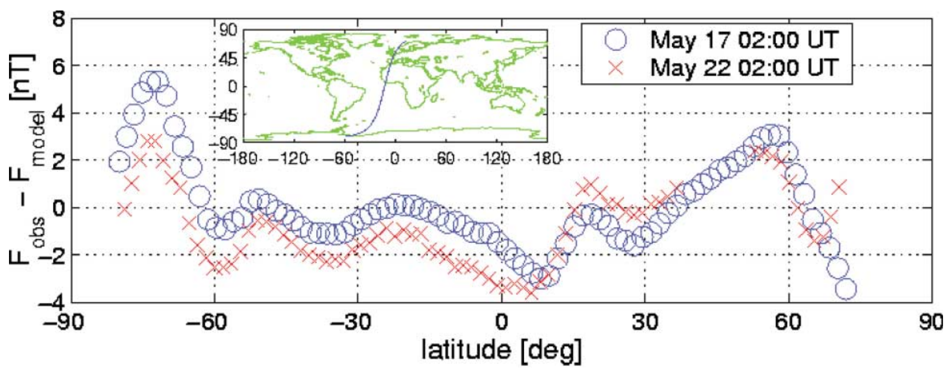

Fig. 2. Comparison of the residuals of two Ørsted orbits along almost identical passes.

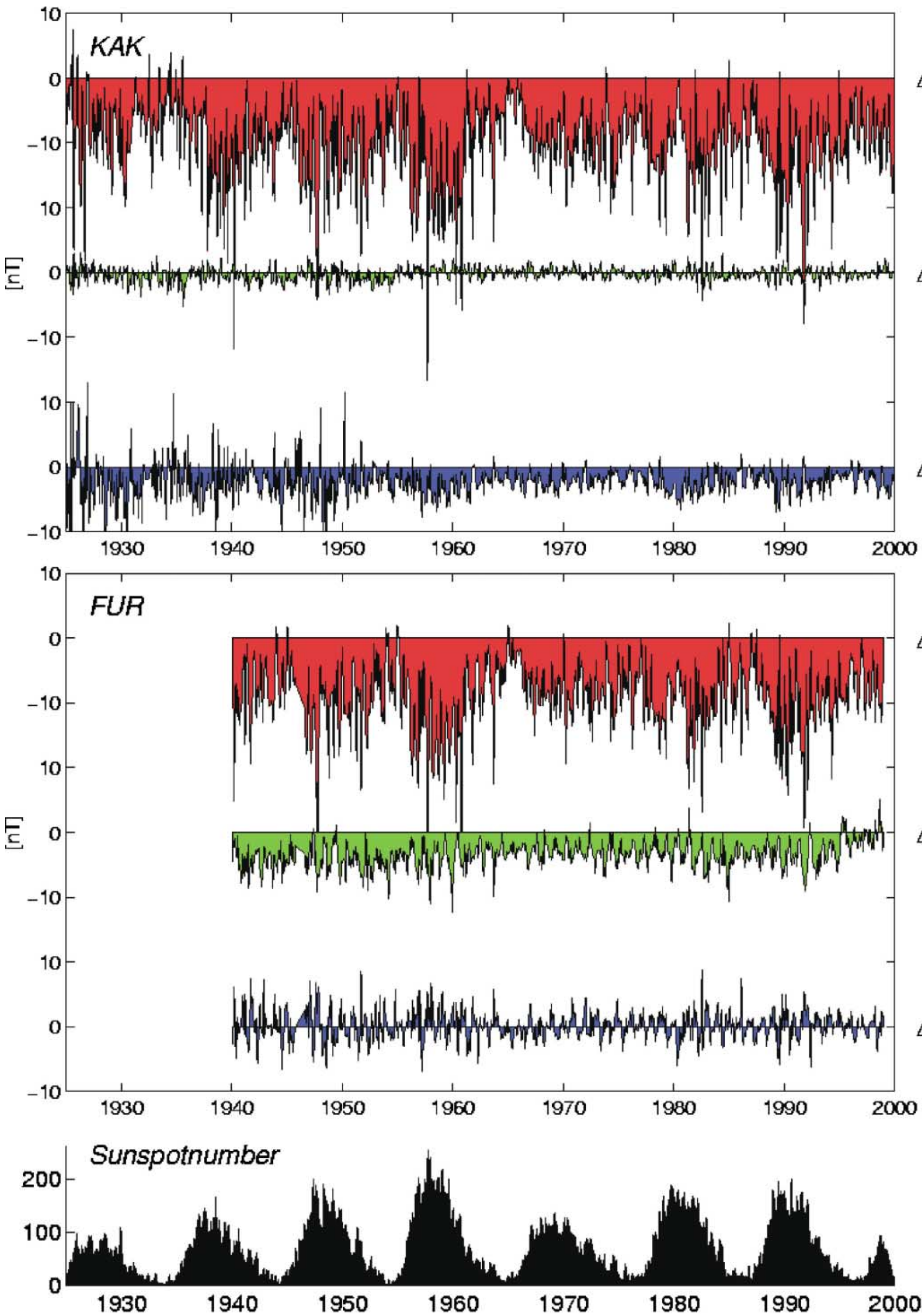

Fig. 3. Time series of the difference between usual monthly mean values (calculated from all data) and modified monthly mean values (calculated from night data of the 5 quietest days) for Fürstenfeldbruck (FUR) and Kakioka (KAK). Also shown are the monthly mean values of the sunspot number as an indicator for solar activity.

The scalar residuals of the two passes contain similar patterns; the negative residual at about 10° N latitude is for instance caused by well-known anomalies in West Africa (Toft et al., 1992). Modeling small-scale features like this anomaly requires spherical harmonics of much higher degree and order than those used for this model. It, therefore, does not describe lithospheric anomalies and hence such anomalies show up in the residuals. The difference between the measurements of the two orbits is in general less than 1 nT, which indicates the high quality of the Ørsted measurements. However, the difference is rather systematic (more negative on 22 May in the Southern Hemisphere and more positive in the Northern Hemisphere), and is probably due to an unmodeled large-scale external source.

It is now a common practice to account for external sources when estimating field models from satellite data, for instance by parameterizing them by the *Dst*-index, a measure of the magnetospheric ring-current derived from data of four ground-based observatories. Such an approach was used for the above-mentioned model. However, the *Dst*-index only describes the symmetric part of the ring-current, and there might have been a different ring-current asymmetry during the two days considered here. This would explain the north–south trends in the difference between the two orbits. Therefore, more sophisticated models of external sources have to be used in order to take advantage of the high data quality of the new satellite missions, as will be discussed in the next section.

4. Considering external sources in geomagnetic field modeling

4.1. External source contributions in observatory mean values

The correction of satellite data using ground-based observations, like the *Dst*-index, is one possible way of considering external sources. Geomagnetic observatories, therefore, are important for separating the various sources, even during periods where space-borne magnetic data exist. Observatory monthly or annual mean values are for instance used, either alone or in combination with satellite data, to determine the long-term variation of the core field, known as secular variation. However, the usual procedure of calculating observatory annual (and monthly) mean values by taking the average over all data (geomagnetic quiet as well as disturbed days; all hours of each day) yields values, denoted as $\mathbf{B}_{\text{all days}}^{\text{all hours}}$, that contain contributions from external sources. Since ionospheric and magnetospheric current systems vary both with season and solar activity, the resulting mean values not only reflect the secular variation of core origin (as often assumed) but they are also modulated by solar cycle and seasonal variations. Uncritical use of the usual annual or monthly mean values for studies of the secular variation will produce spurious effects, for instance an apparent 11-year variation of the core field.

This is illustrated in Fig. 3 which shows the difference $\Delta\mathbf{B} = \mathbf{B}_{\text{all days}}^{\text{all hours}} - \mathbf{B}_{\text{Q-days}}^{\text{night}}$ between the monthly mean values, $\mathbf{B}_{\text{all days}}^{\text{all hours}}$, and modified monthly mean values, $\mathbf{B}_{\text{Q-days}}^{\text{night}}$ for the observatories Fürstenfeldbruck (Germany) and Kakioka (Japan), respectively. The modified monthly mean values $\mathbf{B}_{\text{Q-days}}^{\text{night}}$ have been derived by averaging 5 h centered around local midnight of the 5 quietest days of each month (Q-days). This approach reduces the contributions from ionospheric sources because ionospheric conductivity—at least at middle and low latitudes—is drastically reduced during local nighttime, and because the selection of geomagnetic quiet days reduces magnetospheric contributions. The modified monthly mean values, $\mathbf{B}^{\text{night}}_{\text{Q-days}}$, are believed to contain little, if any, external signal, and therefore the difference $\Delta\mathbf{B}$ indicates to what extent the usual monthly mean values are contaminated by external sources.

Consistent for both observatories, the largest discrepancy is seen in the difference of the north component $\Delta X = X^{\text{all hours}}_{\text{all days}} - X^{\text{night}}_{\text{Q-days}}$. Note the very good agreement of ΔX at Fürstenfeldbruck and at Kakioka (correlation coefficient $r=0.89$), indicating that ΔX is caused by a large-scale, global, source. (The correlation of ΔX is much better than that for the monthly mean values of X itself, since the time variation of the latter is dominated by core processes at all length-scales.) ΔX is negative (indicating that $X^{\text{all hours}}_{\text{all days}}$ contains an external signal of negative sign) but varies with solar cycle and with season. The reason for this behavior is the following: ΔX at mid-latitude observatories like Fürstenfeldbruck and Kakioka is mainly caused by the magnetospheric ring-current and by ionospheric *Sq* currents. Both sources produce (at middle latitudes) a *negative* variation of X; the amplitudes are about twice as large during solar maximum compared to solar minimum.

Modified monthly and annual observatory mean values (obtained from local nighttime data on geomagnetic quiet days) are less contaminated by external sources than the usual mean values (obtained by averaging over all data), and therefore they are more suitable for studies of the core field.

This illustrates how important a careful data selection is, for instance for studying secular variation. Averaging over longer intervals (to obtain monthly or annual means) is often not enough for excluding external contributions; a careful pre-selection of the data prior to averaging is necessary.

4.2. Comprehensive modeling: a new approach of analyzing the near-Earth's magnetic field

Selection of data periods during which external sources are believed to be negligible (or at least small), together with a correction for external sources (for instance the correction for the magnetospheric ring-current signature using the *Dst*-index in the model shown in Fig. 2) is the traditional approach of geomagnetic field modeling. Such a scheme, however, can introduce spurious features, especially when the spatial and temporal scales of the fields overlap. Comprehensive modeling is a new method of co-estimating the magnetic fields from all these sources. The most recent version of the *Comprehensive Model* (Sabaka et al., in press) has been derived from quiet-time Magsat and POGO satellite and observatory hourly and annual-mean values. In total, over 500,000 data points are utilized for the estimation of more than 16,000 model parameters. The result of this effort is a model for which the fits to the data are generally superior to previous models and for which the parameter states for the various constituent sources are very reasonable.

Core- and crustal-fields are described in this model by a spherical harmonic expansion (up to degree/order 65) and the secular variation of the core field (coefficients up to degree/order 13) is described by cubic B-splines in time. Magnetospheric contributions are modeled spatially by spherical harmonics and temporally by trigonometric functions describing the daily and seasonal variations.

Special effort has been put into a proper parameterization of contributions from horizontal currents in the ionospheric *E*-layer (at about 110 km altitude). These currents vary with local time, universal time, season and solar cycle, and their spatial behavior is strongly influenced by the geometry of the main geomagnetic field. To utilize that, a new set of basis functions has been constructed and the spatial expansion was done using these functions instead of spherical harmonics. By doing so, the number of terms needed to describe ionospheric contributions is drastically reduced.

Coupling currents between the ionosphere and the magnetosphere or between the southern and northern hemispheric ionosphere produce a toroidal magnetic field that is only observable at satellite altitude. The present version of the *Comprehensive Model* includes an expansion of this toroidal field (using the same new basis functions as for the ionospheric part). This allows for the use of satellite vector data that have traditionally been excluded (East component at equatorial latitudes, East and South component at polar latitudes) since they are known to be contaminated by non-potential field contributions.

The introduction of this new set of geomagnetically defined basis functions is one example of physical information that was used to constrain the *Comprehensive Model*. Another example is the use of a model of mantle conductivity that links each time-varying external (ionospheric or magnetospheric) term with the corresponding internal (electromagnetic induced) term. Finally, a proper separation of long-period (quasi-static) ionospheric and internal coefficients was achieved by down-weighting ionospheric currents during nighttime, which is justified by the drastically reduced nighttime ionospheric conductivity. For this purpose the integral of the squared ionospheric currents over a patch of 120 degrees longitudinal width centered on the midnight meridian was minimized when estimating the model parameters.

As an example of the ability of the *Comprehensive Model* to describe the various sources, Fig. 4 shows the fit of the model to the magnetic vertical (Z) and East (Y) component observed by the Magsat satellite as a function of latitude. The data are from a pass that was not used in the derivation of the model. Shown is a suite of residual plots for Y (top) and Z (bottom). The top panel of each suite shows residuals (squares) with respect to the main field (up to spherical harmonic degree and order 13), and the line represents the magnetospheric part as predicted by the model. The next panel presents residuals with respect to main and magnetospheric field, and the line now indicates the ionospheric part of the model. This contribution is also removed from the observations, resulting in the squares of the third panel. Although the main-field as well as magnetospheric and ionospheric contributions have been removed, a clear signature in Y at low latitudes remains. This is due to electrical currents at satellite altitude (about 450 km), which produce a toroidal magnetic field. Whereas such a field contributes to the Y component, Z is not affected by a toroidal magnetic field. The *Comprehensive Model*, which is probably the first geomagnetic field model that includes an expansion of the toroidal magnetic field, is able to describe even that feature, and the bottom panel of each suite (subtraction of the core, magnetospheric, ionospheric, and—in the case of Y—also of the toroidal field contribution) represents the remaining signal, which is due to the crustal field (the line) and instrumental noise.

The ability of the *Comprehensive Model* to describe the various sources that contribute to the Earth's magnetic field makes it a valuable tool for geomagnetic research. Studying the lithospheric field using aeromagnetic data, for instance, requires the subtraction of the core and external field contributions prior to data interpretation. This can be obtained with the *Comprehensive Model*. Another application is the probing of mantle conductivity from space. All contributions but the inducing (external) and induced (internal) have to be subtracted from the satellite data, and the *Comprehensive Model* has been successfully used for this purpose.

One of the limitations of the present version of the *Comprehensive Model* is its stationarity; it does not, for instance, account for the day-to-day variability of ionospheric sources. A "dynamic" model is only feasible when simultaneous measurements at different places (both at ground and in space) are available. This requires multi-point missions. The necessity of space-borne multi-point

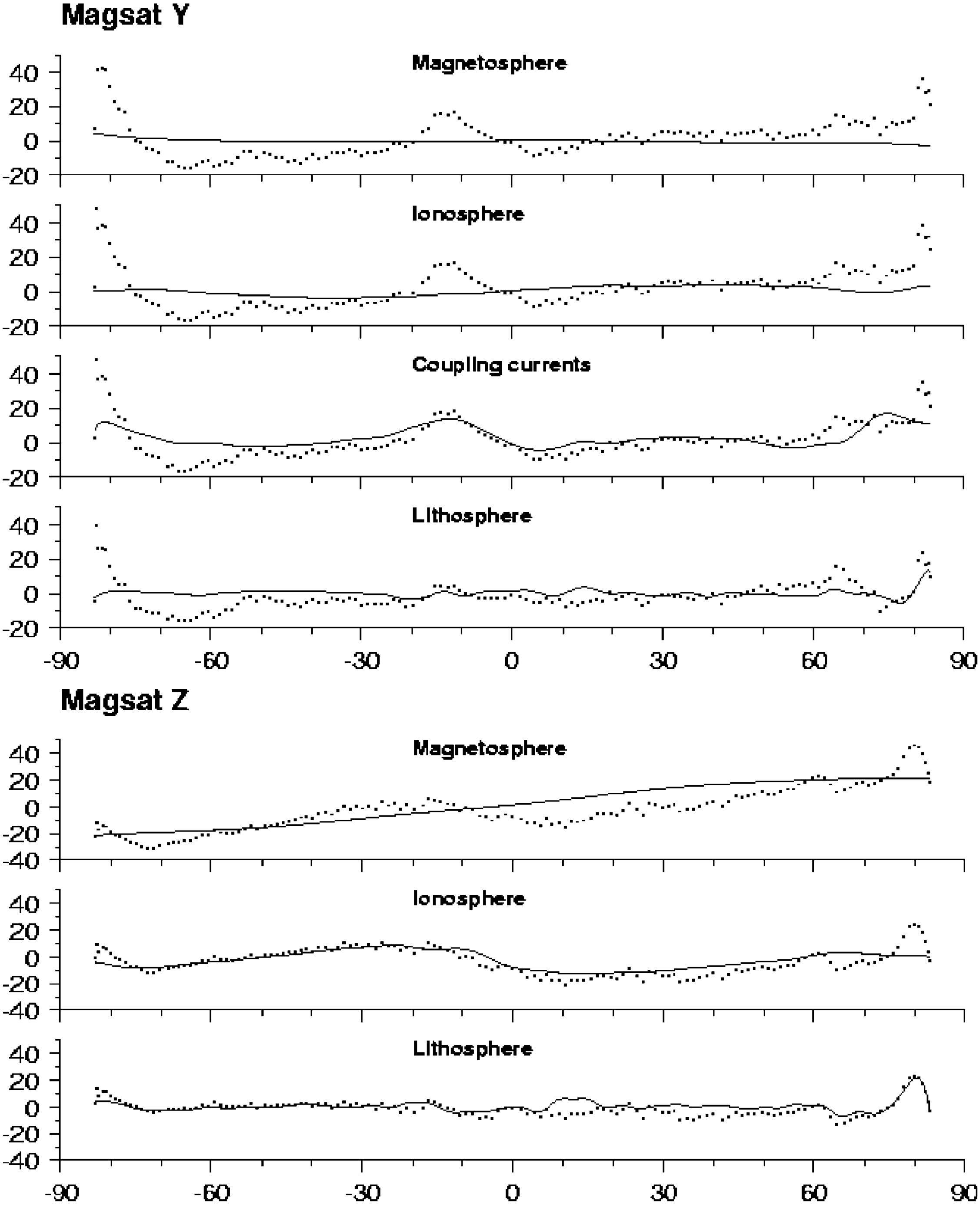

Fig. 4. Residuals (observations minus model values) of Magsat orbit 263 wrt. the comprehensive model. The progression is from the top to bottom member, with a given member showing residuals (squares) with respect to the main field plus all preceding labeled fields and the component (black line) of the predicted, currently labeled field. The upper part is for the Y component; the bottom panel is for the Z component. All ordinates are in nT. The satellite crosses the equator at 129° W.

observations for magnetospheric studies is well established and has motivated the launch of the four Cluster satellites[1] in summer 2000. A corresponding near-Earth multi-point mapping mission is now required. A first step in that direction is provided by the three satellites Ørsted, CHAMP and Ørsted-2/SAC-C.

5. Multi-satellite missions

Recent progress in modeling the Earth's magnetic field indicates that the limiting factor in the accuracy of present geomagnetic models is the dynamic behavior of the external current configuration. Single satellite missions are not able to describe this in a satisfactory way. Models derived with data from single satellite missions can therefore not be obtained with accuracy better than a few nT, which is exceeded by the accuracy of the current instrumentation. Hence, single satellite missions are not able to profit from the enormous improvement of the instruments that has been achieved during the last years. Multiple satellite missions measuring simultaneously over different regions of the Earth offer the only way to take full advantage of this new generation of instruments. It enables a *monitoring* of the time-variability of the geomagnetic field. This is a great advancement compared to the *extrapolations* based on statistics and ground observations at selected sites, which is currently used.

Realizing the potential and timeliness of a multi-satellite mission and in response to a call for proposals for ESA's *Earth Explorer Opportunity Missions* in 1998 a team including the major institutes in Europe concerned with geomagnetic research proposed to undertake a global survey of the geomagnetic field. The unique mission concept called *swarm*[2] is based on a constellation of 6 satellites providing high-precision and high-resolution vector magnetic field measurements in two different orbit planes. In this way it will be possible to acquire the necessary observations for an adequate global survey of the geomagnetic field. The data will be used to derive the most accurate models of the various contributions to the Earth's magnetic field by taking maximum advantage of the sophisticated modeling methods that have recently been developed with this aim in mind.

Such a mission facilitates the analysis of the spatial structure of the time evolution of Earth's magnetic field at large scale lengths (of several thousands of km) as well as at intermediate scale lengths (hundreds of km) and time-scales between seconds and years. The combined analysis of the data obtained with the proposed set of satellites will drastically enhance the signal-to-noise ratio in the extraction of the various sources of the field, enabling a unique separation, thereof. The redundancy inherent in the mission will help secure a long mission lifetime of at least one satellite, answering the need for long-term, order of solar cycle, monitoring of the geomagnetic field. Together with the previous single satellite missions it will, in addition, be possible to derive models of the contribution from external sources that covers a full solar cycle. This will enable re-analysis of data from previous satellites at lower altitude.

In the rigorous international reviewing process the *swarm* proposal received a very high ranking, among the top five of the 27 submitted proposals. Unfortunately the mission was not selected

[1] The four Cluster satellites explore the Earth's magnetic environment at distances between 4 and 20 Earth radii. More information about Cluster can be found at http://sci.esa.int/cluster.

[2] The *swarm* proposal and additional material can be found at http://www.dsri.dk/solsys/swarm.

for immediate implementation. In the meantime the Ørsted and subsequent missions with high precision geomagnetic data have demonstrated the potential of such measurements and also that the scientific society is well prepared to enter the next major step in geomagnetic field research.

5.1. An example of multi-point observations: simultaneous observations of the auroral electrojets with OGO-2 and OGO-4

The most significant ionospheric contribution to the magnetic field occurs in the Polar Regions, where field aligned currents flow between the outer magnetosphere and the polar ionosphere. These currents are driven by the interaction between the solar wind and the Earth's magnetosphere. The associated magnetic field variations exhibit large temporal and spatial fluctuations but occur almost exclusively in the components perpendicular to the direction of the main field. Consequently, the usual way to eliminate this source in geomagnetic field modeling has been to use only scalar measurements, rather than full vector data, at high latitudes.

Other ionospheric sources comprise the horizontal currents that are associated with the field-aligned currents. These currents flow in the ionosphere at an altitude of approximately 110 km. For usual low-Earth orbits the distance between the satellite and the ionosphere implies that the contribution from these currents is comparatively much smaller than that from the (in situ) field-aligned currents. However, the most intense currents, the so-called auroral electrojets, flow in the east-west direction in a rather narrow band in the auroral zone. They give rise to magnetic field variations that have a component along the field lines. This signal is thus present in the absolute field measurements and is therefore not eliminated by the common approach of omitting high-latitude vector measurements for modeling the geomagnetic field.

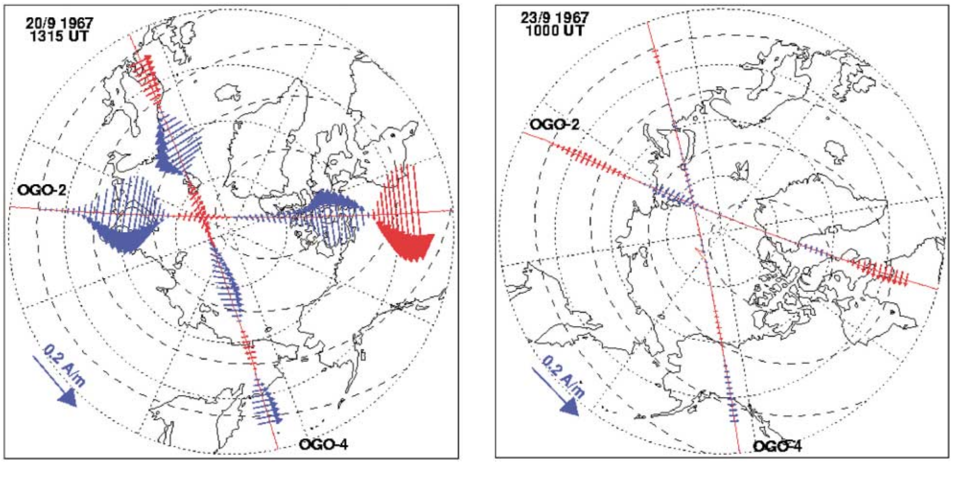

Fig. 5. The estimated cross-track ionospheric currents for simultaneous North polar passes of the OGO-2 and OGO-4 satellites. The two panels are for two different events, the times of which are marked in the top left corner of each panel. The currents are drawn as arrows along the satellite ground track. The length of each arrow reflects the intensity of the current density at that position. In addition, the arrows are colored so that inferred currents flowing mostly westward are shown in red and those flowing mostly eastward in blue. The orientation of each map is such that local noon is at the top. Dashed curves mark the traces of constant geomagnetic latitude of 50, 60, 70 and 80°, respectively.

On the other hand these variations can be used to study and model the auroral electrojet currents. This is demonstrated in Fig. 5. We have used the method described in Olsen (1996) with simultaneous absolute magnetic field measurements from the OGO-2 and OGO-4 satellites to obtain estimates of the cross-track component of the horizontal ionospheric current density along the tracks of the satellites. This was done for two times of very different levels of geomagnetic activity at which the two satellites make simultaneous crossings of the North Polar region. The left panel shows the currents derived during an active period. Most prominent are the westward electrojet over northern Canada and the eastward electrojet north of Russia, which are observed by OGO-2. They are both located at the expected geomagnetic latitude of approximately 65°. Furthermore, the OGO-4 measurements show that the eastward electrojet extends into the afternoon region and that there are no currents observed in the night sector, indicating that this is not the time of a substorm. The differences observed between the OGO-2 and OGO-4 measurements clearly illustrate the importance of multi-spacecraft observations to obtain the detailed picture of these current systems. The right panel illustrates a later simultaneous overpass when the geomagnetic activity level is very low. Here almost no magnetic variations, and hence no ionospheric currents, are detected. This is the case for all four northern auroral zone crossings made by the two satellites. While the current systems exhibit large spatial structure they are also clearly subject to overall variations in intensity reflecting the level of global geomagnetic activity.

6. Summary

The launch of the Ørsted satellite in 1999 marked the beginning of a new era in geomagnetic research. Two additional missions (CHAMP and Ørsted-2/SAC-C) were launched about a year later, as geomagnetic milestones of the *International Decade of Geopotential Research*. The analysis of the data from these missions has demonstrated that it is now possible to measure the magnetic components in space with an accuracy of better than 3 nT.

Of special importance is the joint interpretation of simultaneous measurements from more than one satellite, to obtain a better description of the time-space structure of external sources. Multiple satellite missions measuring simultaneously over different regions of the Earth offer the only way to take full advantage of the enormous improvement in instrumentation that has been achieved during the last years.

However, the development and application of new strategies for geomagnetic field research is also needed. There is a great advantage of modeling Earth's core field and its secular variation together with crustal, ionospheric and magnetospheric contributions in a comprehensive approach. This is done by a joint inversion of ground-based and satellite magnetic measurements. Such an approach provides a potential for very fruitful interaction between scientists representing "internal field science" and "external field science" beyond the usual division into these two subdisciplines. The obtained *Comprehensive Model* turned out to be a valuable tool for research in other geomagnetic disciplines, like studies of electromagnetic induction, or of the lithospheric field.

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