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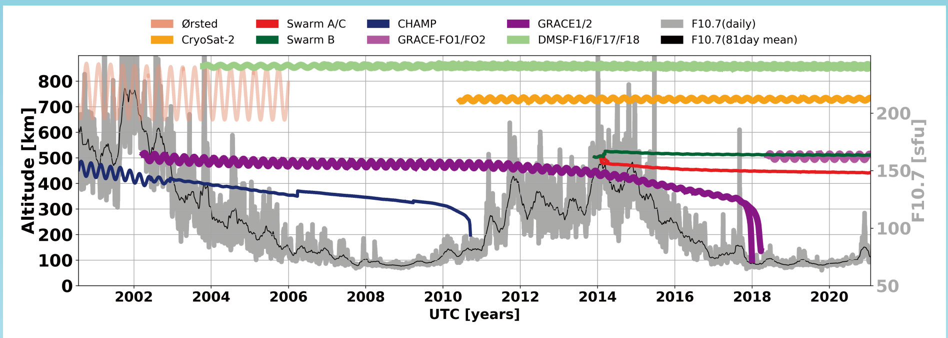
Characterization of the Geomagnetic Field and Its Dynamic Environment Using Data from Space-Based Magnetometers



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PREFACE

Open Access

Special issue "Characterization of the geomagnetic field and its dynamic environment using data from space-based magnetometers"

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The main part of the geomagnetic field arises from electric currents in the Earth's outer core. It extends to a distance of ∼ 10 Earth radii and acts as a shield for protecting our atmosphere against solar and cosmic particle radiation. It also determines the strength and geometry of ionospheric and magnetospheric current systems. While the Earth's core field varies on time scales of months to years, electric currents in the ionosphere and magnetosphere change within seconds to days, e.g., during space weather events. Continuous monitoring of the various magnetic field variations is thus important to characterize the Earth's space environment and ensure the preparedness of modern technology on the ground and in space on which society increasingly depends.

Most of our knowledge of the spatial and temporal variations of the recent geomagnetic field has been obtained using observations taken by high precision magnetic satellite missions, such as Ørsted, CHAMP, and currently the European Space Agency's (ESA) magnetic field constellation mission *Swarm*. However, a multitude of satellites in low Earth orbit (LEO) carry magnetometers that, by design, do not meet the accuracy of dedicated geomagnetic missions. These are avionic, so-called platform magnetometers that are primarily used for coarse attitude determination of the spacecraft. Another category is magnetometers meant for science applications mounted on a boom, but those missions often neither measure the absolute magnetic field intensity together with the variations of the magnetic components nor provide precise attitude determination of the magnetometer itself. However, magnetic data from these missions have been shown to add valuable information in characterizing the geomagnetic field and its environment after appropriate calibration.

This special issue collects articles that document successful calibration strategies including the validation of their results, e.g., by comparison to other data or applied in exemplary science cases, and articles that outline valuable research application in Earth and space sciences by the use of these magnetometer data. Figure 1 shows the altitude distribution of the satellite missions, which data were analyzed in papers of this special issue. In combination, they provide a multi-mission data set in LEO spanning almost two solar cycles.

Extending the calibration scheme developed and applied to data from high-precision satellite missions, Olsen et al. (2020) introduce an approach for characterization, calibration, and alignment of vector magnetometer data, applied to data from the platform magnetometers onboard ESA's CryoSat-2 satellite. The calibration is performed by comparing the magnetometer sensor readings with magnetic field values for the time and position of the satellite as given by an a priori high-precision geomagnetic field model, e.g. CHAOS (Finlay et al. 2020), to estimate the magnetometer calibration parameters by solving a least square problem. The calibrated magnetic data show good agreement with

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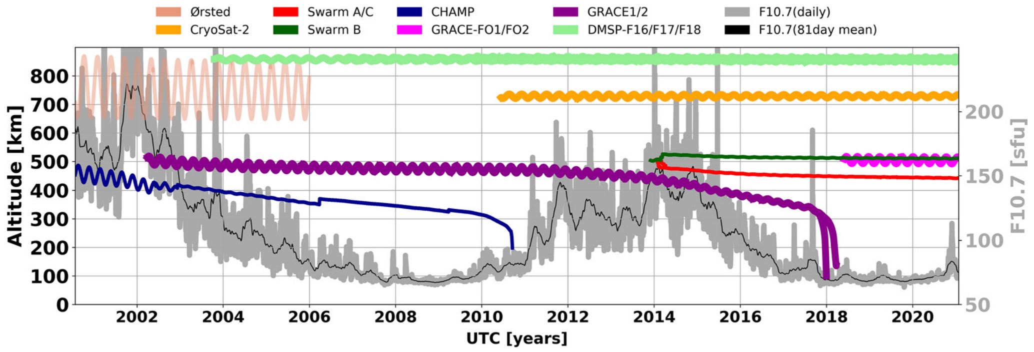

Fig. 1 Altitude of satellite missions used in this special issue (left scale) and solar flux index $F_{10.7}$ (right scale). Altitude of high-precision magnetic missions are plotted by thinner lines, those of others by bolder lines. Altitudes between 26 July 2000 and 24 January 2021 are shown. Ørsted altitudes are shown up to 12/2005 until the mission provided high-precision magnetic data

Swarm satellite magnetic measurements during close encounters. Furthermore, it was demonstrated that the CryoSat-2 magnetic variations follow well the *Dst*-index during a geomagnetic storm event.

Stolle et al. (2021) applied a similar least-square fit to platform magnetometer data of the GRACE-FO dual-satellite constellation mission. The average mean of the remaining residuals to the CHAOS model used in the calibration process show standard deviations below 10 nT rms, which are similar to those derived for CryoSat-2. By combining the *Swarm*, GRACE-FO, and CryoSat-2 satellites, the authors showed that the extended "constellation" does well capture the local time evolution of the magnetospheric ring current under geomagnetic storm conditions. Also, GRACE-FO-derived auroral field-aligned currents compare well in amplitude with those derived from *Swarm* data. The pearls-on-a-string configuration of the GRACE-FO mission further allows scale analyses of ionospheric structures.

Olsen (2021) extended the scheme to process and calibrate the platform magnetometer data of the GRACE dual-satellite mission. The remaining residuals to the models are somewhat higher than those for CryoSat-2 and GRACE-FO due to lacking direct measurements of magnetometer temperature and the rather coarse 12-bit discretization of the GRACE magnetometers; however, the data have been proven relevant for geophysical applications in publications mentioned below. Besides, by combining data from the *Swarm*, GRACE, and CryoSat-2 satellites in spherical harmonic (SH) analyses, the author confirms that the local time asymmetric part of the magnetospheric ring current after the peak of a geomagnetic storm decays faster compared to its symmetric part.

Alken et al. (2020) provide the Frontier Letter for this special issue. They describe a novel scheme for co-estimating magnetometer calibration parameters together with a model of Earth's magnetic field. This method does not require an a priori geomagnetic field model such as CHAOS but relies on supporting calibrated magnetic data, here provided by CHAMP, *Swarm*, and ground observatories. The authors apply this scheme to calibrate magnetic data from the DMSP and CryoSat-2 missions to enhance the description of the rapid core field evolution when satellite-based high-precision magnetic data were not available, e.g., during the gap period between CHAMP and *Swarm* in 2010–2013 (see Fig. 1).

Kloss et al. (2021) present a similar approach, go further, and co-estimate both the internal (core) and the external (magnetospheric) part of geomagnetic field models along with magnetometer calibration parameters. By that, they derive a geomagnetic field model spanning 2008 to 2018 with satellite magnetic data from CHAMP, *Swarm*, data from ground observatories, and platform magnetometer data from CryoSat-2 and the GRACE satellite pair. It was proven that platform magnetometer data provide additional information on the secular acceleration, especially in the Pacific Ocean region during the gap between CHAMP and *Swarm*.

Hammer et al. (2021) use time series of geomagnetic secular variation at 300 globally distributed geomagnetic virtual observatories to study time variations of the Earth's core magnetic field both at satellite altitude and at the core–mantle boundary. They use 20 years of continuous magnetic field measurements from the Ørsted, CHAMP, and *Swarm* satellite missions and calibrated platform magnetometer data from the CryoSat-2 satellite. The authors find that CryoSat-2 platform magnetometer data provide a valuable contribution to emerging pictures of regional sub-decadal core field variations.

Velímský and Knopp (2021) and Kuvshinov et al. (2021) use up to 6 years of contemporaneous magnetic observations of *Swarm* and CryoSat-2 to determine the three-dimensional (3-D) structure of mantle conductivity. The largest benefit from combining the missions was through the enhanced coverage of local time sectors at same observational periods. In their works, the teams followed different approaches.

Velímský and Knopp (2021) perform time-domain forward and inverse electromagnetic (EM) induction modeling to the latest version of satellite-derived time series of SH coefficients of external (inducing) and internal (induced) parts of the magnetic potential describing signals of magnetospheric origin. The inclusion of CryoSat-2 platform magnetometer data had only small influence on the inversion results, but allow for a larger reduction of the data misfit in the applied inversion. The authors recovered large-scale conductivity structures (parameterized by SH up to degree 3) in Earth's mantle, which partially overlap with the shape of the large low-shear velocity provinces in the lower mantle.

Kuvshinov et al. (2021) rely on the estimation and inversion of the so-called matrix *Q*-responses, which relate in the frequency domain the SH coefficients of inducing and induced parts of the magnetic potential. Their results show a significant deviation of mantle conductivity distribution from the global 1-D conductivity profile in the Pacific Ocean region. In their outlook, the authors emphasized the need for the data from more and better distributed (in terms of local time coverage) satellite missions; this will allow for an improved description of the source geometry in the ionosphere and magnetosphere, the prerequisite for future advances in global 3-D EM mapping of mantle conductivity.

Looking at studies of ionospheric current systems, Xiong et al. (2020) compare auroral field-aligned currents (FAC) derived from magnetic data of the DMSP mission with simultaneous energetic particle fluxes detected at the same spacecraft. They performed the first statistical study of these parameters' relation from simultaneous data and found systematic differences in the location of peaks of particle energy flux and large-scale FACs, emphasizing the complexity of the auroral oval region. Furthermore, during conjunction events, the DMSP field-aligned currents were proven to be similar in amplitude with *Swarm*-derived results further supporting their value for space science.

Park et al. (2020) demonstrate that calibrated platform magnetic data can also be used in statistical investigations of low amplitude ionospheric currents at non-polar latitudes. From vertical currents detected during 8 years at CryoSat-2 and during nearly 2 years at GRACE-FO the authors successfully derive global pattern of interhemispheric FACs, the distribution of which is dominated by seasonal variations and tidal forcing from the lower atmosphere. They further discussed that the direction of the currents is systematic southward throughout the year in the South Atlantic sector due to the predominant geometry and relatively low strength of the magnetic field in that region. The paper provides observational evidences of noontime dynamo currents at the highest altitude (of about 700 km, sampled by CryoSat-2) reported so far.

In conclusion, appropriately calibrated data from non-dedicated magnetometers onboard LEO satellites have high value for both Earth's and space research. Examples include (1) filling periods of unavailability of high-precision data, (2) the combination of several missions to a "constellation" for better spatio-temporal coverage, and (3) the availability of geomagnetic observations at multiple platforms, which provides an extended opportunity to perform combined analysis with other ionospheric parameters sampled by particular missions. It is nonetheless noteworthy that these magnetic data have been calibrated along with high-precision observations or using high-resolution geomagnetic field models derived from measurements by the *Swarm* satellites. Simultaneous data from at least one dedicated high-precision magnetic satellite mission thus remain crucial for this endeavor.

Abbreviations

CHAMP: CHAllenging Minisatellite Payload; CHAOS: CHAmp Ørsted SAC-C magnetic field model; DMSP: Defense Meteorological Satellite Program; *Dst*: Geomagnetic Equatorial Disturbance Storm Time Index; EM: Electromagnetic; ESA: European Space Agency; FAC: Field-Aligned Currents; GRACE(-FO): Gravity Recovery and Climate Experiment (-Follow-On); LEO: Low Earth Orbit; rms: Root Mean Square; SH: Spherical Harmonic; 1-D: One-dimensional; 3-D: Three-dimensional.

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Authors' contributions

All authors of this article served as guest editors for this special issue. All authors read and approved the final manuscript.

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Declarations

Competing interests

The authors declare that they have no competing interests.

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Publisher's Note

FRONTIER LETTER Open Access

Co-estimation of geomagnetic field and in-orbit fluxgate magnetometer calibration parameters

Patrick Alken*, Nils Olsen and Christopher C. Finlay

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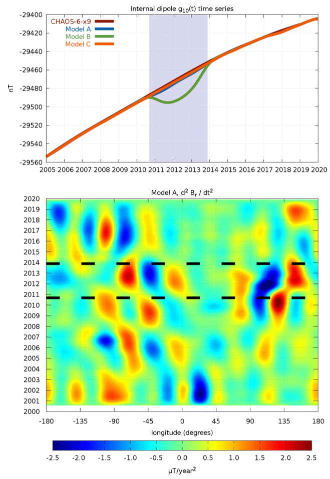
Abstract

For the past 20 years, state of the art geomagnetic core field models have relied heavily on magnetic measurements made from space-based instrumentation. These models have revealed rapid global magnetic field variations on sub-decadal timescales originating in Earth's core. With the end of the CHAMP mission in 2010 and the launch of Swarm in late 2013, there has been a 3-year gap in high-quality satellite measurements of the geomagnetic field. Geomagnetic field models have therefore relied on ground observatory data to fill in this gap period. However, ground observatories are unable to provide a truly global picture of the core field and its temporal changes. Many satellites in operation carry vector fluxgate "platform" magnetometers for attitude control, which can offer an alternative to relying on ground observatory measurements during the gap period. However, these instruments need to be carefully calibrated in order to provide meaningful information on Earth's core field. Some previous studies attempted to calibrate such instruments with a priori geomagnetic field models. This approach has several disadvantages: (1) errors in the model will introduce errors in the calibration parameters, and (2) relying on an a priori model may not be feasible in the post-Swarm era. In this paper, we develop a novel approach to build a time-dependent geomagnetic field model from platform magnetometer data, by co-estimating their calibration parameters with the internal field parameters. This method does not require an a priori geomagnetic field model, but does require a dataset of previously calibrated data. We use CHAMP, Swarm, and ground observatory measurements to supply this dataset, and incorporate platform magnetic measurements from DMSP and Cryosat-2 during the gap years. We find that the calibration parameters of DMSP and Cryosat-2 can be reliably estimated, and these missions provide meaningful information on rapid core field variations during the gap period.

Keywords: Geomagnetism, Core field modeling, Secular variation, Secular acceleration, Fluxgate calibration, Inverse theory



Graphical abstract

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FULL PAPER Open Access

Magnetic observations from CryoSat-2: calibration and processing of satellite platform magnetometer data

Nils Olsen*, Giuseppe Albini, Jerome Bouffard, Tommaso Parrinello and Lars Tøffner-Clausen

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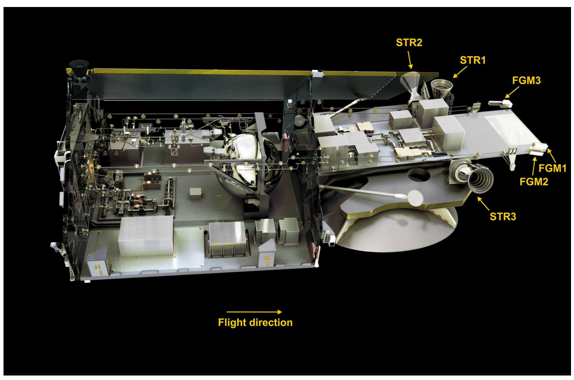
Abstract

We describe and discuss the preprocessing and calibration steps applied to the magnetic data measured by the three "platform magnetometers" on-board the CryoSat-2 satellite. The calibration is performed by comparing the magnetometer sensor readings with magnetic field values for the time and position of the satellite as given by the CHAOS-6 geomagnetic field model. We allow for slow temporal variations of the calibration parameters by solving for scale values, offsets, and non-orthogonalities in monthly bins, and account for non-linearities as well as the magnetic disturbances caused by battery, solar panel and magnetorquer currents. Fully calibrated magnetic vector data, together with time and position, are provided as daily files in CDF data format at swarm-diss.eo.esa.int. The data show good agreement with *Swarm* satellite magnetic measurements during close encounters (rms difference between 1 and 5 nT for inter-satellite distances below 300 km).

Keywords: Geomagnetism, Magnetic satellites, Magnetometer calibration, CryoSat-2



Graphical abstract

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FULL PAPER **Open Access**

Relationship between large-scale ionospheric field-aligned currents and electron/ion precipitations: DMSP observations

Chao Xiong*, Claudia Stolle, Patrick Alken and Jan Rauberg

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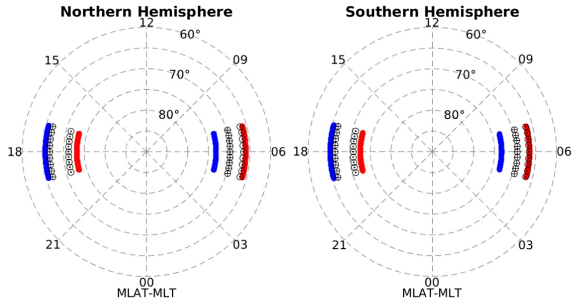
Abstract

In this study, we have derived field-aligned currents (FACs) from magnetometers onboard the Defense Meteorological Satellite Project (DMSP) satellites. The magnetic latitude versus local time distribution of FACs from DMSP shows comparable dependences with previous findings on the intensity and orientation of interplanetary magnetic field (IMF) B_y and B_z components, which confirms the reliability of DMSP FAC data set. With simultaneous measurements of precipitating particles from DMSP, we further investigate the relation between large-scale FACs and precipitating particles. Our result shows that precipitation electron and ion fluxes both increase in magnitude and extend to lower latitude for enhanced southward IMF B_z, which is similar to the behavior of FACs. Under weak northward and southward B_z conditions, the locations of the R2 current maxima, at both dusk and dawn sides and in both hemispheres, are found to be close to the maxima of the particle energy fluxes; while for the same IMF conditions, R1 currents are displaced further to the respective particle flux peaks. Largest displacement (about 3.5°) is found between the downward R1 current and ion flux peak at the dawn side. Our results suggest that there exists systematic differences in locations of electron/ion precipitation and large-scale upward/downward FACs. As outlined by the statistical mean of these two parameters, the FAC peaks enclose the particle energy flux peaks in an auroral band at both dusk and dawn sides. Our comparisons also found that particle precipitation at dawn and dusk and in both hemispheres maximizes near the mean R2 current peaks. The particle precipitation flux maxima closer to the R1 current peaks are lower in magnitude. This is opposite to the known feature that R1 currents are on average stronger than R2 currents.

Keywords: Field-aligned currents, Aurora, Particle precipitation, DMSP



Graphical abstract

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FULL PAPER **Open Access**

Diagnosing low-/mid-latitude ionospheric currents using platform magnetometers: CryoSat-2 and GRACE-FO

Jaeheung Park*, Claudia Stolle, Yosuke Yamazaki, Jan Rauberg, Ingo Michaelis and Nils Olsen

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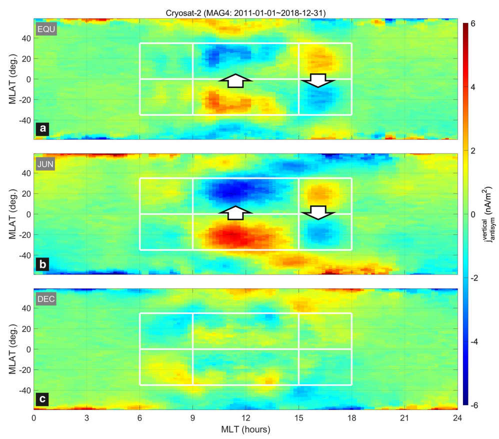
Abstract

Electric currents flowing in the terrestrial ionosphere have conventionally been diagnosed by low-earth-orbit (LEO) satellites equipped with science-grade magnetometers and long booms on magnetically clean satellites. In recent years, there are a variety of endeavors to incorporate platform magnetometers, which are initially designed for navigation purposes, to study ionospheric currents. Because of the suboptimal resolution and significant noise of the platform magnetometers, however, most of the studies were confined to high-latitude auroral regions, where magnetic field deflections from ionospheric currents easily exceed 100 nT. This study aims to demonstrate the possibility of diagnosing weak low-/mid-latitude ionospheric currents based on platform magnetometers. We use navigation magnetometer data from two satellites, CryoSat-2 and the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO), both of which have been intensively calibrated based on housekeeping data and a high-precision geomagnetic field model. Analyses based on 8 years of CryoSat-2 data as well as ~ 1.5 years of GRACE-FO data reproduce well-known climatology of inter-hemispheric field-aligned currents (IHFACs), as reported by previous satellite missions dedicated to precise magnetic observations. Also, our results show that C-shaped structures appearing in noontime IHFAC distributions conform to the shape of the South Atlantic Anomaly. The F-region dynamo currents are only partially identified in the platform magnetometer data, possibly because the currents are weaker than IHFACs in general and depend significantly on altitude and solar activity. Still, this study evidences noontime F-region dynamo currents at the highest altitude (717 km) ever reported. We expect that further data accumulation from continuously operating missions may reveal the dynamo currents more clearly during the next solar maximum.

Keywords: Platform magnetometers, CryoSat-2, GRACE-FO, Inter-hemispheric field-aligned currents, F-region dynamo currents



Graphical abstract

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FULL PAPER **Open Access**

Lateral variations of electrical conductivity in the lower mantle constrained by Swarm and CryoSat-2 missions

Jakub Velímský* and Ondřej Knopp

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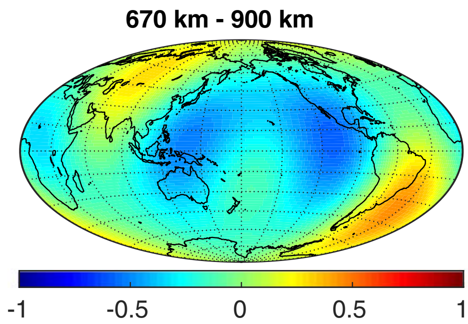
Abstract

The electrical conductivity is an important geophysical parameter connected to the thermal, chemical, and mineralogical state of the Earth's mantle. In this paper, we apply the previously developed methodology of forward and inverse EM induction modeling to the latest version of satellite-derived spherical harmonic coefficients of external and internal magnetic field, and obtain the first 3-D mantle conductivity models with contributions from Swarm and CryoSat-2 satellite data. We recover degree 3 conductivity structures which partially overlap with the shape of the large low-shear velocity provinces in the lower mantle.

Keywords: EM induction, Mantle electrical conductivity, Swarm, CryoSat-2



Graphical abstract

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FULL PAPER **Open Access**

Co-estimating geomagnetic field and calibration parameters: modeling Earth's magnetic field with platform magnetometer data

Clemens Kloss*, Christopher C. Finlay and Nils Olsen

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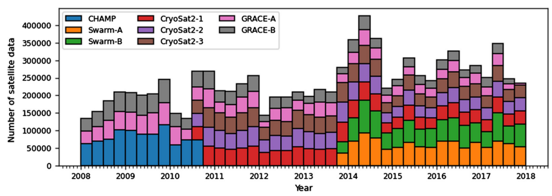
Abstract

Models of the geomagnetic field rely on magnetic data of high spatial and temporal resolution to give an accurate picture of the Earth's internal magnetic field and its time-dependence. The magnetic data from low-Earth orbit satellites of dedicated magnetic survey missions such as CHAMP and *Swarm* play a key role in the construction of such models. Unfortunately, there are no magnetic data available from such satellites after the end of the CHAMP mission in 2010 and before the launch of the *Swarm* mission in late 2013. This limits our ability to recover signals on timescales of 3 years and less during this gap period. The magnetic data from platform magnetometers carried by satellites for navigational purposes may help address this data gap provided that they are carefully calibrated. Earlier studies have demonstrated that platform magnetometer data can be calibrated using a fixed geomagnetic field model as reference. However, this approach can lead to biased calibration parameters. An alternative approach has been developed in the form of a co-estimation scheme which consists of simultaneously estimating both the calibration parameters and a model of the internal part of the geomagnetic field. Here, we go further and develop a scheme, based on the CHAOS field modeling framework, that involves co-estimation of both internal and external geomagnetic field models along with calibration parameters of platform magnetometer data. Using our implementation, we are able to derive a geomagnetic field model spanning 2008 to 2018 with satellite magnetic data from CHAMP, *Swarm*, secular variation data from ground observatories, and platform magnetometer data from CryoSat-2 and the GRACE satellite pair. Through a number of experiments, we explore correlations between the estimates of the geomagnetic field and the calibration parameters, and suggest how these may be avoided. We find evidence that platform magnetometer data provide additional information on the secular acceleration, especially in the Pacific during the gap between CHAMP and *Swarm*. This study adds to the evidence that it is beneficial to use platform magnetometer data in geomagnetic field modeling.

Keywords: Geomagnetism, Core field modeling, Inverse theory, Secular acceleration, Secular variation



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FULL PAPER **Open Access**

Observing Earth's magnetic environment with the GRACE-FO mission

C. Stolle*, I. Michaelis, C. Xiong, M. Rother, Th. Usbeck, Y. Yamazaki, J. Rauberg and K. Styp-Rekowski

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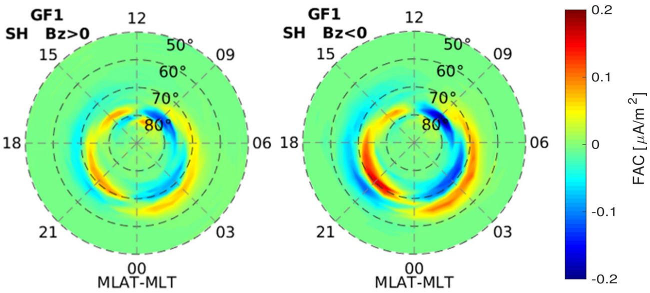
Abstract

The Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission carries magnetometers that are dedicated to enhance the satellite's navigation. After appropriate calibration and characterisation of artificial magnetic disturbances, these observations are valuable assets to characterise the natural variability of Earth's magnetic field. We describe the data pre-processing, the calibration, and characterisation strategy against a high-precision magnetic field model applied to the GRACE-FO magnetic data. During times of geomagnetic quiet conditions, the mean residual to the magnetic model is around 1 nT with standard deviations below 10 nT. The mean difference to data of ESA's Swarm mission, which is dedicated to monitor the Earth's magnetic field, is mainly within ± 10 nT during conjunctions. The performance of GRACE-FO magnetic data is further discussed on selected scientific examples. During a magnetic storm event in August 2018, GRACE-FO reveals the local time dependence of the magnetospheric ring current signature, which is in good agreement with results from a network of ground magnetic observations. Also, derived field-aligned currents (FACs) are applied to monitor auroral FACs that compare well in amplitude and statistical behaviour for local time, hemisphere, and solar wind conditions to approved earlier findings from other missions including Swarm. On a case event, it is demonstrated that the dual-satellite constellation of GRACE-FO is most suitable to derive the persistence of auroral FACs with scale lengths of 180 km or longer. Due to a relatively larger noise level compared to dedicated magnetic missions, GRACE-FO is especially suitable for high-amplitude event studies. However, GRACE-FO is also sensitive to ionospheric signatures even below the noise level within statistical approaches. The combination with data of dedicated magnetic field missions and other missions carrying non-dedicated magnetometers greatly enhances related scientific perspectives.

Keywords: Earth's magnetic field, Geomagnetism, Ionospheric currents, Magnetospheric ring current, Satellite-based magnetometers, Platform magnetometers, GRACE-FO



Graphical abstract

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FULL PAPER **Open Access**

Magnetometer data from the GRACE satellite duo

Nils Olsen

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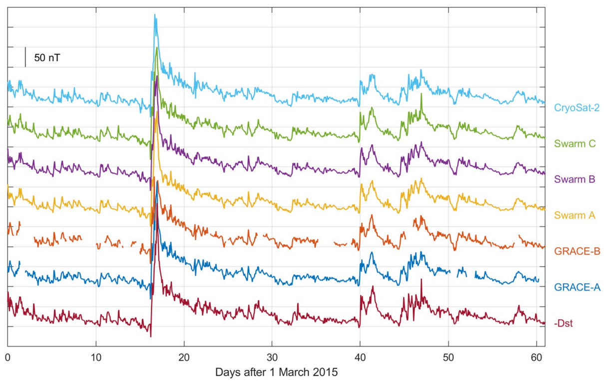
Abstract

This paper describes and discusses the preprocessing and calibration of the magnetic data taken by the navigational magnetometers onboard the two GRACE satellites, with focus on the almost 10 years period from January 2008 to the end of the GRACE mission in October 2017 for which 1-Hz magnetic data are available. A calibration of the magnetic data is performed by comparing the raw magnetometer sensor readings with model magnetic vector values as provided by the CHAOS-7 geomagnetic field model for the time and position of the GRACE data. The presented approach also accounts for magnetic disturbances produced by the satellite's magnetorquer and for temperature effects, which are parametrized by the Sun incident angle. The root-mean-squared error of the difference between the calibrated data and CHAOS-7 model values is about 10 nT, which makes the GRACE magnetometer data relevant for geophysical investigations.

Keywords: Geomagnetism, Magnetic satellites, Magnetometer calibration, GRACE satellites



Graphical abstract

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Probing 3-D electrical conductivity of the mantle using 6 years of Swarm, CryoSat-2 and observatory magnetic data and exploiting matrix Q-responses approach

Alexey Kuvshinov*, Alexander Grayver, Lars Tøffner-Clausen and Nils Olsen

Earth, Planets and Space 2021, **73**:67 DOI: 10.1186/s40623-020-01341-9
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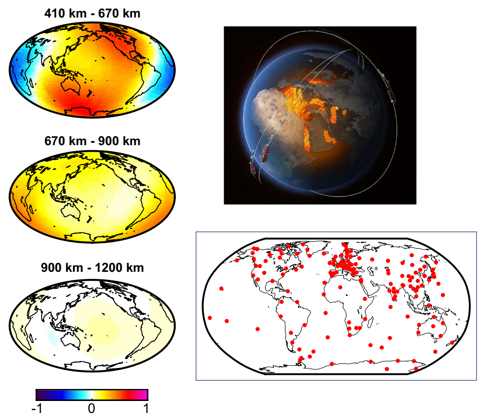
Abstract

This study presents results of mapping three-dimensional (3-D) variations of the electrical conductivity in depths ranging from 400 to 1200 km using 6 years of magnetic data from the *Swarm* and CryoSat-2 satellites as well as from ground observatories. The approach involves the 3-D inversion of matrix Q-responses (transfer functions) that relate spherical harmonic coefficients of external (inducing) and internal (induced) origin of the magnetic potential. Transfer functions were estimated from geomagnetic field variations at periods ranging from 2 to 40 days. We study the effect of different combinations of input data sets on the transfer functions. We also present a new global 1-D conductivity profile based on a joint analysis of satellite tidal signals and global magnetospheric Q-responses.

Keywords: Electromagnetic induction, Three-dimensional conductivity models, Matrix Q-responses, Inversion, Time-varying magnetic field, Magnetospheric ring-current source, Satellite data, Observatory data



Graphical abstract

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FULL PAPER Open Access

Applications for CryoSat-2 satellite magnetic data in studies of Earth's core field variations

Magnus D. Hammer*, Christopher C. Finlay and Nils Olsen

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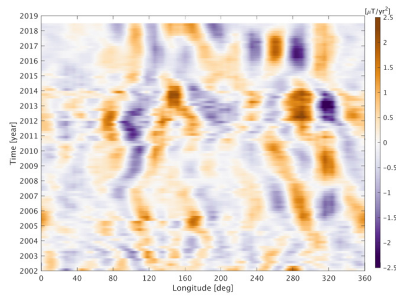
Abstract

We use 20 years of continuous magnetic field measurements from the Ørsted, CHAMP and *Swarm* satellite missions, supplemented by calibrated platform magnetometer data from the CryoSat-2 satellite, to study time variations of the Earth's core field at satellite altitude and at the core–mantle boundary (CMB). From the satellite data we derive composite time series of the core field secular variation (SV) with 4-month cadence, at 300 globally distributed Geomagnetic Virtual Observatories (GVO). A previous gap in the GVO series between 2010 and 2014 is successfully filled using CryoSat-2, and sub-decadal variations are identified during this period. Tests showed that similar sub-decadal SV patterns were obtained from the CryoSat-2 data regardless of whether IGRF-13 or CHAOS-6x9 was used in their calibration. Cryosat-2 radial field SV series at non-polar latitudes have a mean standard deviation level compared to smoothing spline fits of 3.5 nT/yr compared to 1.8 nT/yr for CHAMP and 0.9 nT/yr for *Swarm*. GVO radial SV series display regional fluctuations with 5–10 years duration and amplitudes reaching 20 nT/yr, most notably at low latitudes over Indonesia (2014), over South America and the South Atlantic (2007, 2011 and 2014), and over the central Pacific (2017). Applying the Subtractive Optimally Localized Averages (SOLA) method, we also map the radial SV at the CMB as a collection of locally averaged SV estimates. We demonstrate that using 2-year windows of CryoSat-2 data, it is possible to reliably estimate the SV and its time derivative, the secular acceleration (SA), at the CMB, with a spatial resolution, corresponding to spherical harmonic degree 10. Along the CMB geographic equator, we find strong SA features with amplitude ±2.5 μT/yr^2 under Indonesia from 2011–2014, under central America from 2015 to 2019, and sequences of SA with alternating sign under the Atlantic during 2004–2019. We find that platform magnetometer data from CryoSat-2 make a valuable contribution to the emerging picture of sub-decadal core field variations. Using 1-year windows of data from the *Swarm* satellites, we show that it is possible to study SA changes at low latitudes on timescales down to 1 year, with spatial resolution corresponding to spherical harmonic degree 10. We find strong positive and negative SA features appearing side-by-side in the Pacific in 2017, and thereafter drift westward.

Keywords: Geomagnetism, Secular variation, Secular acceleration, Earth's core, Platform magnetometer, CryoSat-2 satellite Swarm satellite constellation



Time-longitude plot of the secular acceleration along the geographical equator at the core-mantle boundary derived from Ørsted, CHAMP, CryoSat-2 and Swarm magnetic data.

Graphical abstract

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Information for Contributors

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Contents

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