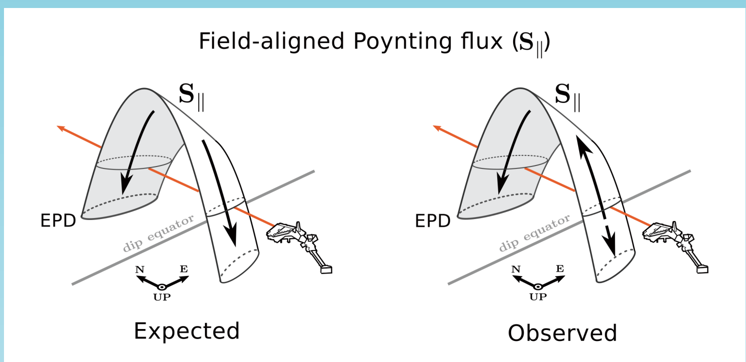
Earth, Planets and Space

DynamicEarth: Earth's Interior, Surface, Ocean, Atmosphere, and Near Space Interactions



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The Seismological Society of Japan
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Japan Geoscience Union

SpringerOpen

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Earth, Planets and Space (EPS) is the official journal of Society of Geomagnetism and Earth, Planetary and Space Sciences, The Seismological Society of Japan, The Volcanological Society of Japan, The Geodetic Society of Japan, and The Japanese Society for Planetary Sciences.
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Yours sincerely,

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Stolle *et al. Earth, Planets and Space* (2023) 75:137
https://doi.org/10.1186/s40623-023-01893-6

PREFACE

Open Access

Special issue "DynamicEarth: Earth's interior, surface, ocean, atmosphere, and near space interactions"

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The near-Earth's gravity and magnetic fields are most important to enable terrestrial life. The role of the gravity field is obvious, it reflects the mass distribution of the Earth's interior and determines, e.g., the flow of water. The role of the geomagnetic field is more indirect. It protects our atmosphere from severe solar and cosmic radiation. Mankind's capability to measure the gravity and geomagnetic fields has been fundamentally important to advance societal development since hundreds of years (e.g., navigation) and it has brought scientific breakthroughs in several disciplines of geosciences recently (e.g., response of ground water tables to natural climate variability and anthropogenic water use, characteristics of solar–terrestrial interactions in the magnetosphere and space weather).

Variations in Earth's interior, atmosphere, oceans, and near-Earth space manifest in the gravity and Earth's magnetic fields and their changes. Understanding the spatial and temporal characteristics of these potential fields requires knowledge of the all these Earth's components. In turn, observations of the geomagnetic and the gravitational fields provide a wealth of information about them. An interdisciplinary approach is thus most effective to best exploit new observations and advanced modelling capabilities. The Priority Programme 1788 "DynamicEarth" funded by the German Research Foundation (DFG) between 2015 and 2021 has established an international research framework for gravity, geomagnetism, space and atmospheric sciences to tackle the interdisciplinary questions. This special issue collects contributions that exploit data from recent dedicated satellites in low Earth orbit, such as ESA's Swarm mission launched in 2013 and the US/German GRACE-FO mission launched in 2018, among others. It also addresses studies based on ground-based observations and on empirical and numerical models which concerns one or more of these geoscientific research areas.

A global geomagnetic field model derived from data of several satellites, as well as ground, airborne and ship data is provided by Baerenzung et al. (2022). At well covered regions, the model reaches resolutions up to spherical harmonic degree and order 1000, and temporally down to 3 h. It thus emphasises on the representation of the lithospheric field. Another model advancement lies in the joint estimation of the magnetospheric fields and those induced in the mantle and crust. Oceanic magnetic signals are expected to provide valuable information on climatological trends in the ocean. Their extraction from geomagnetic measurements requires, however, high-precision estimates from other magnetic field sources. Petereit et al. (2022) used 10 years of geomagnetic ground-based observations to investigate the

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seasonal variations and long-term trends of oceanic lunar tide. An increased specification of errors in estimating oceanic tidal signals by applying the model infrastructure described in Baerenzung et al. (2022) from this special issue is discussed in Saynisch-Wagner et al. (2021). Differently to oceanic tides, signals from ocean circulation are very challenging to detect in magnetic observations due to their long-term variability combined with their low amplitude, but still could provide an approach towards better understanding ocean climate evolution. To this aim, Hornschild et al. (2022) evaluated a new algorithm for detecting magnetic signals of ocean circulation on a synthetic data set.

Space- and ground-based geomagnetic observations combined with, e.g, electric field, plasma density and drift, and solar wind data are crucial to investigate the magnetosphere–ionosphere interactions and, in addition, are essential in characterising signal properties from magnetospheric sources. To complement the Swarm data base of magnetic measurements, Michaelis et al. (2022) and Styp-Rekowski et al. (2022) presented calibrated magnetic data from non-dedicated instruments onboard ESA's GOCE satellite mission by an analytical and by a Machine Learning technique, respectively. Their results demonstrate the high value and quality of the data from this low-flying satellite (about 260 km altitude) by successful applications in imaging magnetic signatures of the lithospheric field and deciphering the local time dependence of magnetospheric ring current signals. Xiong et al. (2021) exploited recently non-dedicated calibrated magnetometer data of the GRACE-FO twin satellite mission which flies in a string-of-pearls constellation. They derived characteristic correlations lengths of magnetic disturbances due to auroral field-aligned currents. By the combination of solar wind, geomagnetic, and ionospheric data and indices, Rout et al. (2022) identified a global magnetosphere–ionosphere quasi-resonant mode of oscillation during long-duration auroral geomagnetic activity.

At the mid- and low-latitude ionosphere, high-precision satellite-based geomagnetic observations are used to investigate ionospheric currents which result from a close interaction with neutral dynamics in the lower thermosphere and atmosphere, and with the geomagnetic field. Rodríguez-Zuluaga et al. (2022) provide the frontier letter of this special issue identifying the source of low-latitude post-sunset F region plasma irregularities to be off-equatorial which is in contrast to earlier theories suggesting equatorial sources. This observational evidence was achieved by analysing the 3-component Swarm magnetic field measurements and the derived hypothesis was verified with a local physics-based model of ionospheric irregularities. Concerning regular, periodic variability, Yamazaki (2022) provides a comprehensive study of solar and lunar daily geomagnetic variations and their equivalent ionospheric current systems in the E region including their quantification. Only available from ground-based, locally restricted data so far, this paper provides a global view on atmospheric tides in the magnetic field based on Swarm observations. Sporadic-E events are E region ionospheric irregularities and they, as well as post-sunset equatorial F region irregularities, can disturb trans-ionospheric radio waves used for navigation, such as GNSS, severely through their strong imprint in local plasma density gradients. Arras et al. (2022) discussed generation mechanisms for the rarely observed equatorial Sporadic-E events based on GPS radio occultation data from multiple satellites, while Sobhkhiz-Miandehi et al. (2022) identified tidal variations in the occurrence of mid-latitude Sporadic-E events based on GPS radio occultation of the FORMOSAT-3/COSMIC mission and compared the observations with results from a whole-atmosphere General Circulation Model (GCM).

Parameterised imaging of the regular global ionospheric plasma density is provided by Lalgudi Gopalakrishnan and Schmidt (2022). Also their work relies on electron density profiles derived from GPS observations onboard the GRACE and the FORMOSAT-3/COSMIC missions supported by in situ electron density data from several missions. Validation with independent ionosonde data revealed a correlation between observations and their parameterised images of the ionospheric F region peak height up to 90%. The variability of neutral winds and temperature in the Mesosphere–Lower Thermosphere (MLT) largely determine the variability of the entire ionosphere, e.g., by the propagation of atmospheric tides and waves. Thus, the MLT is a major link in vertical atmosphere coupling. Based on globally distributed, satellite-based neutral temperature data and results from a whole-atmosphere GCM, Siddiqui et al. (2022) described the reduction of low-latitude solar tides at the MLT during both Northern and Southern stratospheric warming events. They suggested that changes in the latitudinal shear in the MLT could explain the observed variability. Based on a synthetic data set for a network of radar stations, He (2023) reviewed existing analysis schemes and introduced a new scheme for the derivation of planetary waves in the MLT winds, as well as compared the implications of the schemes on the analysis results. Applying a spectral analysis on a data set from a radar network campaign in northern Germany, Charuvil Asokan et al. (2022) provided evidence that gravity waves with periods between 2 and 7 h dominate horizontal medium-scale structures of neutral winds in the MLT.

Several of the works in this special issue rely on a most accurate performance of GCMs of the upper atmosphere. As a step forward towards a most realistic representation of neutral and electron density in GCMs, Corbin and Kusche (2022) and Fernandez-Gomez et al. (2022) proposed data assimilation approaches of CHAMP, GRACE, and Swarm neutral density data into a GCM and could demonstrate the improvement of the model predictions of neutral and electron density, respectively.

Only a multi-disciplinary approach from disciplines in geophysics, meteorology, geodesy, and theoretical developments can reveal a better understanding of the complex variability of Earth's magnetic and gravity fields including the various sources of this variability, e.g., in the Earth's interior, oceans, magnetosphere, and atmosphere. The presented papers give valuable examples of fruitful interdisciplinary research in solar–terrestrial science and provide ground for new approaches.

Abbreviations

CHAMP	CHAllenging Minisatellite Payload
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
ESA	European Space Agency
GCM	General Circulation Model
GNSS	Global Navigation Satellite Systems
GOCE	Gravity field and steady-state OCean circulation Explorer
GPS	Global Positioning System
GRACE(-FO)	GRavity Recovery and Climate Experiment (-Follow-On)
MLT	Mesosphere–lower thermosphere

Acknowledgements
We express our sincere gratitude to the authors who contributed to this special issue and the reviewers who evaluated the contributions and gave thoughtful comments and suggestions. We also thank Editor-in-Chief Takeshi Sagiya for his support in editing the issue. Particular acknowledgement is given to the German Research Foundation (DFG) for the installation of the Priority Programme 1788 "Dynamic Earth" supporting many of the joint research activities and published works, as well as to the external review panel for their thorough and constructive evaluation of the research project proposals.

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

Funding
This initiative has been partly supported by projects in the Priority Programme 1788 "Dynamic Earth" funded by the German Research Foundation (DFG).

Availability of data and materials
Not applicable.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 7 July 2023 Accepted: 29 August 2023
Published online: 12 September 2023

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Publisher's Note

FRONTIER LETTER **Open Access**

Topside equatorial spread *F*-related field-aligned Poynting flux: observations and simulations

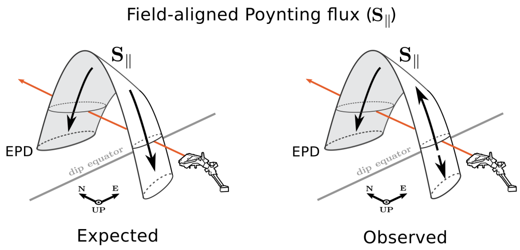
J. Rodríguez-Zuluaga*, C. Stolle, D. Hysell and D. J. Knudsen

Earth, Planets and Space 2022, **74**:119 DOI: 10.1186/s40623-022-01679-2
Received: 5 April 2022, Accepted: 14 July 2022, Published: 29 July 2022

Abstract

Electric and magnetic field data from the Swarm constellation mission are used to report on the Poynting flux associated with postsunset topside equatorial spread *F*. A three-dimensional numerical simulation of plasma density irregularities in the *F* region ionosphere leading to spread *F* is used to interpret and support the satellite observations. Here, we focus on quasi-static magnetic and electric fields nearby equatorial plasma depletions (EPDs). The observations show a correlation of the Poynting flux with the plasma number density when background densities are larger than 10^5 cm^{-3}—typical of pre-midnight hours. In other words, the Poynting flux increases as EPDs get more depleted. As time passes, both plasma density and Poynting flux decay. For the latter, however, this temporal dependence is evident in the pre-midnight sector only. Concerning spatial variations, the Poynting flux is observed to enhance inside EPDs as a function of magnetic latitude mainly due to the strengthening of field-aligned currents as they flow away from the dip equator. The Poynting flux follows the dynamo theory, wherein the winds in the *F* region act as the generator at night and the *E* region conductivity on shared magnetic field lines as the load. That said, the Poynting flux is generally expected to flow along the field lines away from a dynamo source at the dip equator. Nevertheless, observations show unidirectional flows from one magnetic hemisphere to another, suggesting a generator below the satellites' altitude. The numerical simulations confirm these observations and show that such latitudinal shifts of the generator are due almost entirely to the winds.

Keywords: Equatorial spread *F*, Plasma density depletions, Poynting flux, Swarm, Spread *F* simulation



Graphical abstract

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FULL PAPER **Open Access**

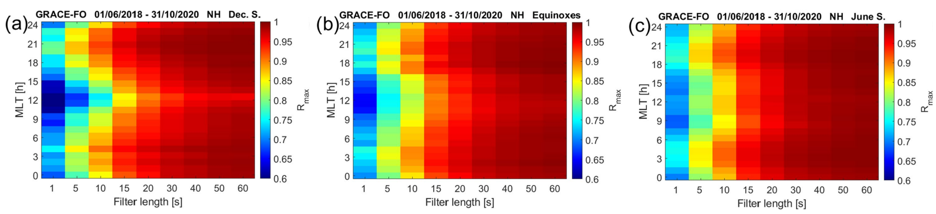
Correlation analysis of field-aligned currents from the magnetic measurements of GRACE follow-on mission

Chao Xiong*, Claudia Stolle, Ingo Michaelis, Hermann Lühr, Yunliang Zhou, Hui Wang, Guram Kervalishvili and Jan Rauberg

Earth, Planets and Space 2021, **73**:206 DOI: 10.1186/s40623-021-01540-y
Received: 7 September 2021, Accepted: 3 November 2021, Published: 15 November 2021

Abstract

In this study we performed a detailed analysis on the scale-size of field-aligned currents (FACs) at auroral latitudes, using the well-calibrated magnetic data from the non-dedicated magnetic field mission, Gravity Recovery and Climate Experiment Follow-On (GRACE-FO). With two spacecraft following each other, the GRACE-FO provides a good opportunity to identify the variation of FACs with different scale lengths. The results show that the auroral FACs can be classified into two groups: the small-scale ones, shorter than some tens of kilometers, dominated by kinetic Alfvén waves, are quite dynamic; and the large-scale ones, typically larger than 150 km, can be considered as quasi-static and persist longer than 1 min. The GRACE-FO observations also reveal that the small-scale FACs at the same location sometimes can persist over 25 s, e.g., around dusk and dawn hours, which is longer than the typical persistent period (10 s) of kinetic Alfvén waves as earlier reported. The FAC structures show clear magnetic local time dependence, with higher correlations between the spacecraft around dusk and dawn hours; lower correlations are found around midnight and lowest correlations around noon, implying that the small-scale FACs most frequently appear at the noon cusp region. Slightly better correlations of FACs between two spacecraft are found during local summer, and such seasonal dependence is dominated by the correlations of small-scale FACs at noon. However, further analysis shows that the small-scale FACs at noon have largest occurrence and intensity during local summer, which reveals that when interpreting the cross-correlation analysis the intensity of FACs needs to be taken into account.



Graphical abstract

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FULL PAPER **Open Access**

Tide-induced magnetic signals and their errors derived from CHAMP and Swarm satellite magnetometer observations

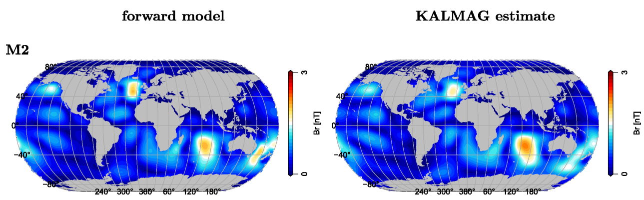
Jan Saynisch-Wagner*, Julien Baerenzung, Aaron Hornschild, Christopher Irrgang and Maik Thomas

Earth, Planets and Space 2021, **73**:234 DOI: 10.1186/s40623-021-01557-3
Received: 15 September 2021, Accepted: 8 December 2021, Published: 20 December 2021

Abstract

Satellite-measured tidal magnetic signals are of growing importance. These fields are mainly used to infer Earth's mantle conductivity, but also to derive changes in the oceanic heat content. We present a new Kalman filter-based method to derive tidal magnetic fields from satellite magnetometers: KALMAG. The method's advantage is that it allows to study a precisely estimated posterior error covariance matrix. We present the results of a simultaneous estimation of the magnetic signals of 8 major tides from 17 years of Swarm and CHAMP data. For the first time, robustly derived posterior error distributions are reported along with the reported tidal magnetic fields. The results are compared to other estimates that are either based on numerical forward models or on satellite inversions of the same data. For all comparisons, maximal differences and the corresponding globally averaged RMSE are reported. We found that the inter-product differences are comparable with the KALMAG-based errors only in a global mean sense. Here, all approaches give values of the same order, e.g., 0.09 nT-0.14 nT for M2. Locally, the KALMAG posterior errors are up to one order smaller than the inter-product differences, e.g., 0.12 nT vs. 0.96 nT for M2.

Keywords: Tides, Electromagnetic induction, Error covariance, Satellite magnetometer observations



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FULL PAPER **Open Access**

On the characterization of tidal ocean-dynamo signals in coastal magnetic observatories

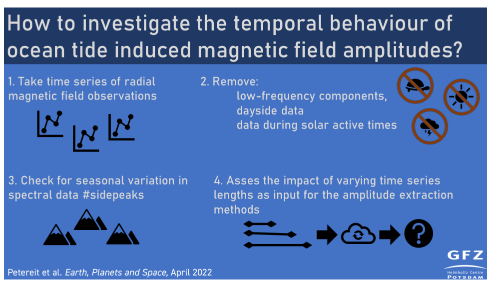
Johannes Petereit*, Jan Saynisch-Wagner, Achim Morschhauser, Leonie Pick and Maik Thomas

Earth, Planets and Space 2022, **74**:67 DOI: 10.1186/s40623-022-01610-9
Received: 22 September 2021, Accepted: 23 March 2022, Published: 29 April 2022

Abstract

Periodic tidal ocean currents induce electric currents and, therefore, magnetic field signals that are observable using spaceborne and ground-based observation techniques. In theory, the signals can be used to monitor oceanic temperature and salinity variations. Tidal magnetic field amplitudes and phases have been extracted from magnetometer measurements in the past. However, due to uncertainties caused by a plentitude of influencing factors, the shape and temporal variation of these signals are only known to a limited extent. This study uses past extraction methods to characterize seasonal variations and long-term trends in the ten year magnetometer time series of three coastal island observatories. First, we assess data processing procedures used to prepare ground-based magnetometer observations for tidal ocean dynamo signal extraction to demonstrate that existing approaches, i.e., subtraction of core field models or first-order differencing, are unable to reliably remove low-frequency contributions. We hence propose low-frequency filtering using smoothing splines and demonstrate the advantages over the existing approaches. Second, we determine signal and side peak magnitudes of the M2 tide induced magnetic field signal by spectral analysis of the processed data. We find evidence for seasonal magnetic field signal variations of up to 25% from the annual mean. Third, to characterize the long-term behavior of tidal ocean dynamo signal amplitudes and phases, we apply different signal extraction techniques to identify tidal ocean-dynamo signal amplitudes and phases in sub-series of the ten-year time series with incrementally increasing lengths. The analyses support three main findings: (1) trends cause signal amplitude changes of up to ≈1 nT and phase changes are in the order of $\mathcal{O}(10°)$ within the observation period; (2) at least four years of data are needed to obtain reliable amplitude and phase values with the extraction methods used and (3) signal phases are a less dependent on the chosen extraction method than signal amplitudes.

Keywords: Ocean-tide induced magnetic fields, Tidal ocean dynamo, EMOTS, Signal extraction, Magnetometer Observations, Data Processing



Graphical abstract

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FULL PAPER **Open Access**

Frequency spectra of horizontal winds in the mesosphere and lower thermosphere region from multistatic specular meteor radar observations during the SIMONe 2018 campaign

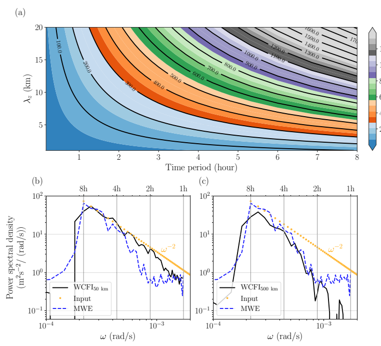
Harikrishnan Charuvil Asokan*, Jorge L. Chau, Raffaele Marino, Juha Vierinen, Fabio Vargas, Juan Miguel Urco, Matthias Clahsen and Christoph Jacobi

Earth, Planets and Space 2022, **74**:69 DOI: 10.1186/s40623-022-01620-7
Received: 7 July 2021, Accepted: 2 April 2022, Published: 11 May 2022

Abstract

In recent years, multistatic specular meteor radars (SMRs) have been introduced to study the Mesosphere and Lower Thermosphere (MLT) dynamics with increasing spatial and temporal resolution. SMRs, compared to other ground-based observations, have the advantage of continuously measuring the region between 80 and 100 km independent of weather, season, or time of day. In this paper, frequency spectra of MLT horizontal winds are explored through observations from a campaign using the SIMONe (Spread-spectrum Interferometric Multistatic meteor radar Observing Network) approach conducted in northern Germany in 2018 (hereafter SIMONe 2018). The 7-day SIMONe 2018 comprised of fourteen multistatic SMR links and allows us to build a substantial database of specular meteor trail events, collecting more than one hundred thousand detections per day within a geographic area of ~500 km × 500 km. We have implemented two methods to obtain the frequency spectra of the horizontal wind components: (1) Mean Wind Estimation (MWE) and (2) Wind field Correlation Function Inversion (WCFI), which utilizes the mean and the covariances of the line of sight velocities, respectively. Monte Carlo simulations of a gravity wave spectral model were implemented to validate and compare both methods. The simulation analyses suggest that the WCFI helps us to capture the energy of smaller scale wind fluctuations than those capture with MWE. Characterization of the spectral slope of the horizontal wind at different MLT altitudes has been conducted on the SIMONe 2018, and it provides evidence that gravity waves with periods smaller than 7 h and greater than 2 h dominate with horizontal structures significantly larger than 500 km. In the future, these analyses can be extended to understand the significance of small-scale fluctuations in the MLT, which were not possible with conventional MWE methods.

Keywords: Frequency spectra, Mesosphere and lower thermosphere, Specular meteor radar, Horizontal winds, Wind field Correlation Function Inversion, SIMONe 2018



Graphical abstract

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FULL PAPER **Open Access**

Comparison of the tidal signatures in sporadic E and vertical ion convergence rate, using FORMOSAT-3/COSMIC radio occultation observations and GAIA model

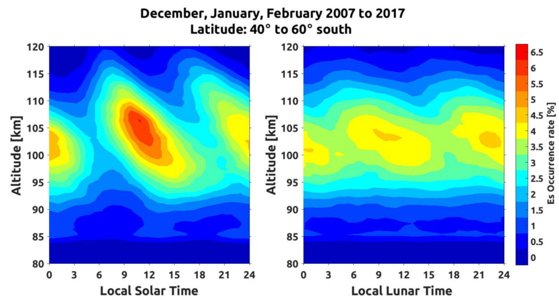
Sahar Sobhkhiz-Miandehi*, Yosuke Yamazaki, Christina Arras, Yasunobu Miyoshi and Hiroyuki Shinagawa

Earth, Planets and Space 2022, **74**:88 DOI: 10.1186/s40623-022-01637-y
Received: 1 November 2021, Accepted: 29 April 2022, Published: 7 June 2022

Abstract

Sporadic E or Es is a transient phenomenon where thin layers of enhanced electron density appear in the ionospheric E region (90–120 km altitude). The neutral wind shear caused by atmospheric tides can lead ions to converge vertically at E-region heights and form the Es layer. This research aims to determine the role of atmospheric solar and lunar tides in Es occurrence. For this purpose, radio occultation data of FORMOSAT-3/COSMIC have been used, which provide complete global coverage of Es events. Moreover, GAIA model simulations have been employed to evaluate the vertical ion convergence induced by solar tides. The results show both migrating and non-migrating solar tidal signatures and the semidiurnal migrating lunar tidal signature mainly in low and mid-latitude Es occurrence. The seasonal variation of the migrating solar tidal components of Es is in good agreement with those in the vertical ion convergence derived from GAIA at higher altitudes. Furthermore, some non-migrating components of solar tides, including semidiurnal westward wavenumbers 1 and 3 and diurnal eastward wavenumbers 2 and 3, also significantly affect the Es occurrence rate.

Keywords: Sporadic E, Es, Wind shear, Solar tide, Lunar tide, GAIA, Radio occultation



Graphical abstract

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FULL PAPER Open Access

Solar and lunar daily geomagnetic variations and their equivalent current systems observed by Swarm

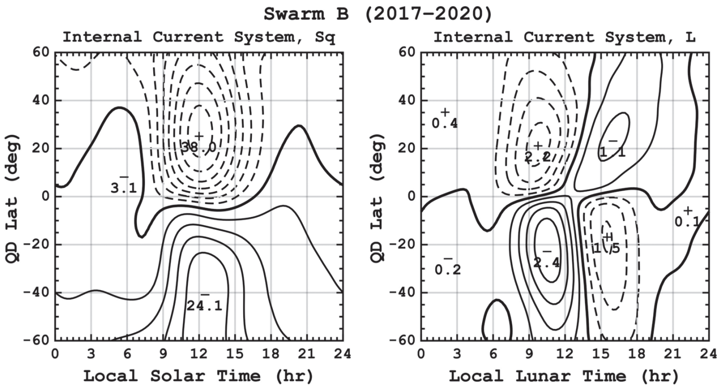
Yosuke Yamazaki

Earth, Planets and Space 2022, **74**:99 DOI: 10.1186/s40623-022-01656-9
Received: 14 February 2022, Accepted: 2 June 2022, Published: 23 June 2022

Abstract

This paper describes solar and lunar daily variations of the geomagnetic field over low- and mid-latitude regions, using vector magnetometer data from Swarm satellites at altitudes of ~500 km during the solar minimum years of 2017–2020. The average solar variation of the geomagnetic field is within the range of ±14 nT, while the lunar variation is within ±2 nT. The latter is comparable to the ocean tidal field. A spherical harmonic analysis is performed on the solar and lunar variations to evaluate their internal and external equivalent current systems. The results show that both the solar and lunar variations are mainly of internal origin, which can be attributed to combined effects of ionospheric dynamo currents and induced underground currents. Global patterns of the internal solar and lunar current systems are consistent with the corresponding external current systems previously reported based on ground observations. The Swarm external currents are mainly in the meridional direction, and are likely associated with interhemispheric field-aligned currents. Both the internal and external current systems depend on the season and longitude.

Keywords: Geomagnetic field, Sq, L, Daily variation, Ionospheric currents, Swarm



Graphical abstract

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FULL PAPER Open Access

Migrating solar diurnal tidal variability during Northern and Southern Hemisphere Sudden Stratospheric Warmings

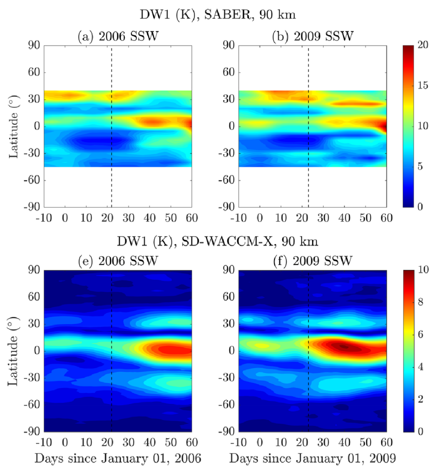
Tarique A. Siddiqui*, Jorge L. Chau, Claudia Stolle and Yosuke Yamazaki

Earth, Planets and Space 2022, **74**:101 DOI: 10.1186/s40623-022-01661-y
Received: 16 February 2022, Accepted: 9 June 2022, Published: 24 June 2022

Abstract

In this study, the variability of the migrating solar diurnal (DW1) tide in the mesosphere-lower thermosphere (MLT) region during Northern and Southern Hemisphere (NH & SH) Sudden Stratospheric Warmings (SSWs) is investigated using Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) temperature observations and reanalysis-driven Whole Atmosphere Community Climate Model with thermosphere and ionosphere extension (WACCM-X) simulations. The periods examined include four major NH SSWs that occurred in 2006, 2009, 2010 and 2013 and two SH SSWs that were observed in 2002 and 2019. Our analysis shows that the DW1 tide in both observations and simulations displays a reduction of amplitude at low-latitudes after the onset of NH and SH SSWs. As WACCM-X simulations qualitatively reproduce this feature of DW1 tidal variability common to both NH and SH SSWs, they have been used to examine the possible mechanism that could explain these observations in the DW1 tide. It is known that changes in the latitudinal shear of zonal winds at low-latitudes strongly affect the seasonal variation of the DW1 tide in the MLT. We show that SSW-associated changes in the latitudinal shear in the MLT could explain the observed variability of the DW1 tide during NH and SH SSWs.

Keywords: SSW, Migrating solar tide, Mesosphere-lower thermosphere (MLT), Atmospheric coupling



Graphical abstract

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FULL PAPER **Open Access**

Improving estimates of the ionosphere during geomagnetic storm conditions through assimilation of thermospheric mass density

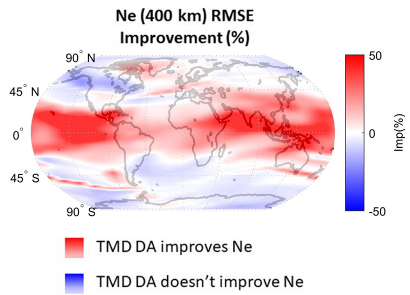
Isabel Fernandez-Gomez*, Timothy Kodikara, Claudia Borries, Ehsan Forootan, Andreas Goss, Michael Schmidt and Mihail V. Codrescu

Earth, Planets and Space 2022, **74**:121 DOI: 10.1186/s40623-022-01678-3
Received: 10 February 2022, Accepted: 14 July 2022, Published: 6 August 2022

Abstract

Dynamical changes in the ionosphere and thermosphere during geomagnetic storm times can have a significant impact on our communication and navigation applications, as well as satellite orbit determination and prediction activities. Because of the complex electrodynamics coupling processes during storms, which cannot be fully described with the sparse set of thermosphere–ionosphere (TI) observations, it is crucial to accurately model the state of the TI system. The approximation closest to the true state can be obtained by assimilating relevant measurements into physics-based models. Thermospheric mass density (TMD) derived from satellite measurements is ideal to improve the thermosphere through data assimilation. Given the coupled nature of the TI system, the changes in the thermosphere will also influence the ionosphere state. This study presents a quantification of the changes and improvement of the model state produced by assimilating TMD not only for the thermosphere density but also for the ionosphere electron density under storm conditions. TMD estimates derived from a single Swarm satellite and the Coupled Thermosphere Ionosphere Plasmasphere electrodynamics (CTIPe) physics-based model are used for the data assimilation. The results are presented for a case study during the St. Patricks Day storm 2015. It is shown that the TMD data assimilation generates an improvement of the model's thermosphere density of up to 40% (measured along the orbit of the non-assimilated Swarm satellites). The model's electron density during the course of the storm has been improved by approximately 8 and 22% relative to Swarm-A and GRACE, respectively. The comparison of the model's global electron density against a high-quality 3D electron density model, generated through assimilation of total electron content, shows that TMD assimilation modifies the model's ionosphere state positively and negatively during storm time. The major improvement areas are the mid-low latitudes during the storm's recovery phase.

Keywords: Data assimilation, Geomagnetic storm, Neutral density, Thermosphere–ionosphere system



Graphical abstract

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FULL PAPER **Open Access**

Machine learning-based calibration of the GOCE satellite platform magnetometers

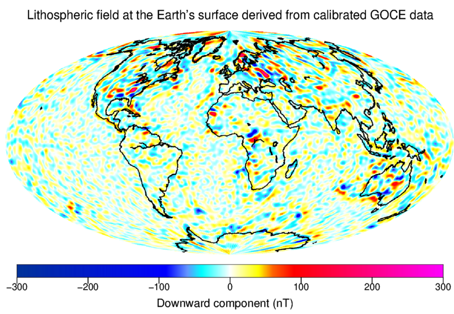
Kevin Styp-Rekowski*, Ingo Michaelis, Claudia Stolle, Julien Baerenzung, Monika Korte and Odej Kao

Earth, Planets and Space 2022, **74**:138 DOI: 10.1186/s40623-022-01695-2
Received: 6 May 2022, Accepted: 24 August 2022, Published: 13 September 2022

Abstract

Additional datasets from space-based observations of the Earth's magnetic field are of high value to space physics and geomagnetism. The use of platform magnetometers from non-dedicated satellites has recently successfully provided additional spatial and temporal coverage of the magnetic field. The Gravity and steady-state Ocean Circulation Explorer (GOCE) mission was launched in March 2009 and ended in November 2013 with the purpose of measuring the Earth's gravity field. It also carried three platform magnetometers onboard. Careful calibration of the platform magnetometers can remove artificial disturbances caused by other satellite payload systems, improving the quality of the measurements. In this work, a machine learning-based approach is presented that uses neural networks to achieve a calibration that can incorporate a variety of collected information about the satellite system. The evaluation has shown that the approach is able to significantly reduce the calibration residual with a mean absolute residual of about 6.47nT for low- and mid-latitudes. In addition, the calibrated platform magnetometer data can be used for reconstructing the lithospheric field, due to the low altitude of the mission, and also observing other magnetic phenomena such as geomagnetic storms. Furthermore, the inclusion of the calibrated platform magnetometer data also allows improvement of geomagnetic field models. The calibrated dataset is published alongside this work.

Keywords: Machine learning, Calibration, Platform magnetometer, GOCE satellite, Magnetic field model



Graphical abstract

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FULL PAPER **Open Access**

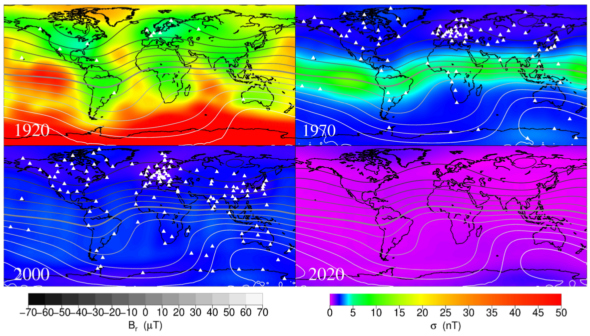
Kalmag: a high spatio-temporal model of the geomagnetic field

Baerenzung Julien*, Holschneider Matthias, Jan Saynisch-Wagner and Maik Thomas

Earth, Planets and Space 2022, **74**:139 DOI: 10.1186/s40623-022-01692-5
Received: 2 April 2022, Accepted: 19 August 2022, Published: 16 September 2022

Abstract

We present the extension of the Kalmag model, proposed as a candidate for IGRF-13, to the twentieth century. The dataset serving its derivation has been complemented by new measurements coming from satellites, ground-based observatories and land, marine and airborne surveys. As its predecessor, this version is derived from a combination of a Kalman filter and a smoothing algorithm, providing mean models and associated uncertainties. These quantities permit a precise estimation of locations where mean solutions can be considered as reliable or not. The temporal resolution of the core field and the secular variation was set to 0.1 year over the 122 years the model is spanning. Nevertheless, it can be shown through ensembles a posteriori sampled, that this resolution can be effectively achieved only by a limited amount of spatial scales and during certain time periods. Unsurprisingly, highest accuracy in both space and time of the core field and the secular variation is achieved during the CHAMP and Swarm era. In this version of Kalmag, a particular effort was made for resolving the small-scale lithospheric field. Under specific statistical assumptions, the latter was modeled up to spherical harmonic degree and order 1000, and signal from both satellite and survey measurements contributed to its development. External and induced fields were jointly estimated with the rest of the model. We show that their large scales could be accurately extracted from direct measurements whenever the latter exhibit a sufficiently high temporal coverage. Temporally resolving these fields down to 3 hours during the CHAMP and Swarm missions, gave us access to the link between induced and magnetospheric fields. In particular, the period dependence of the driving signal on the induced one could be directly observed. The model is available through various physical and statistical quantities on a dedicated website at https://ionocovar.agnld.uni-potsdam.de/Kalmag/.



Graphical abstract

Keywords: Geomagnetic field, Lithospheric field, Secular variation, Magnetospheric field, Induced field, Assimilation, Kalman filter, Machine learning

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FULL PAPER **Open Access**

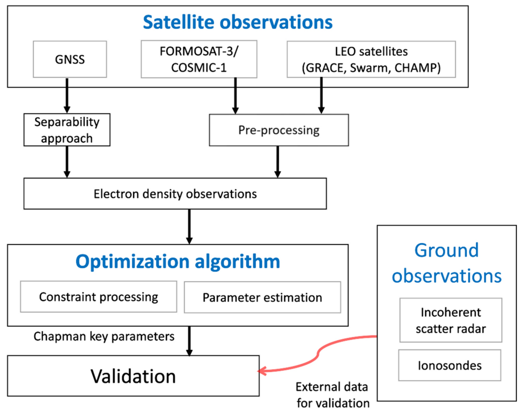
Ionospheric electron density modelling using B-splines and constraint optimization

Ganesh Lalgudi Gopalakrishnan* and Michael Schmidt

Earth, Planets and Space 2022, **74**:143 DOI: 10.1186/s40623-022-01693-4
Received: 5 April 2022, Accepted: 21 August 2022, Published: 19 September 2022

Abstract

Many modern applications, such as precise point positioning, autonomous driving or precision agriculture would benefit significantly if a high-precision and high-resolution model of electron density in the ionosphere and the plasmasphere would be globally available. Since the development of such a model still relies on data with insufficient and uneven global coverage, the consideration of background information and the introduction of equality and inequality constraints on Chapman key parameters are essential. In this work, we develop a multi-layer Chapman model based on B-spline expansions of selected key parameters of the electron density. The unknown series coefficients of the key parameters are subject to equality and inequality constraints. Finally, the developed model is applied to a combination of real and semi-simulated input data; the results are validated through ionosonde measurements.



Graphical abstract

Keywords: Ionosphere layers, Multi-layer Chapman model, Inequality constraints, B-spline expansions, Optimization approach

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FULL PAPER Open Access

Sporadic E layer characteristics at equatorial latitudes as observed by GNSS radio occultation measurements

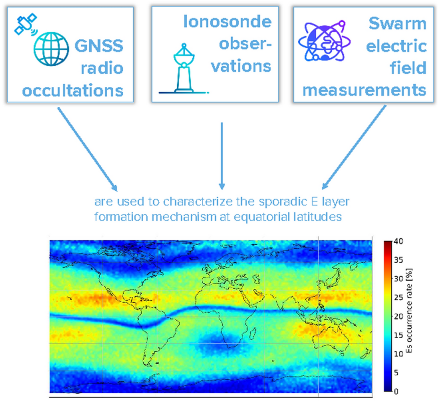
Christina Arras*, Laysa Cristina Araújo Resende, Ankur Kepkar, Gethmini Senevirathna and Jens Wickert

Earth, Planets and Space 2022, **74**:163 DOI: 10.1186/s40623-022-01718-y
Received: 31 March 2022, Accepted: 10 October 2022, Published: 7 November 2022

Abstract

Scintillations in the signal-to-noise (SNR) profiles of GNSS radio occultation (RO) measurements at lower ionospheric altitudes are caused by compact layers of high ionization also known as sporadic E (Es) layers. It is widely accepted that Es layers are formed by the wind shear mechanism at northern and southern midlatitudes. However, approaching the equatorial regions, electric fields also control the formation and dispersal of these layers. In this paper we concentrate, in particular, on the occurrence rate and on the altitudes of Es layers appearing in a narrow band along the Earth's magnetic equator. We analyzed several million of RO profiles concerning sporadic E occurrence as well as altitude and observed a high daily, seasonal and longitudinal variability which is controlled partly by zonal winds and electric fields. Especially Es layers at higher altitudes show a clear anticorrelation with the zonal electric field intensity measured by the Swarm satellites. Further, we solve the existing contradiction of Es layer signatures being present in equatorial ionosonde measurements while they are only rarely seen in RO recordings.

Keywords: GNSS radio occultation, Sporadic E layers, Equatorial ionosphere



Graphical abstract

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FULL PAPER Open Access

On the detectability of the magnetic fields induced by ocean circulation in geomagnetic satellite observations

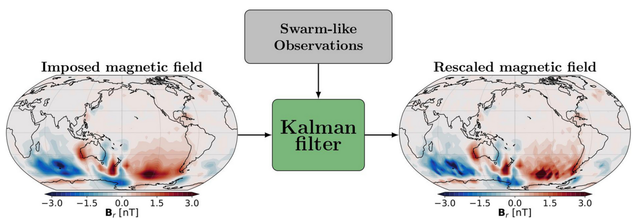
Aaron Hornschild*, Julien Baerenzung, Jan Saynisch-Wagner, Christopher Irrgang and Maik Thomas

Earth, Planets and Space 2022, **74**:182 DOI: 10.1186/s40623-022-01741-z
Received: 16 May 2022, Accepted: 10 November 2022, Published: 9 December 2022

Abstract

Due to their sensitivity to conductivity and oceanic transport, magnetic signals caused by the movement of the ocean are a beneficial source of information. Satellite observed tidal-induced magnetic fields have already proven to be helpful to derive Earth's conductivity or ocean heat content. However, magnetic signals caused by ocean circulation are still unobserved in satellite magnetometer data. We present a novel method to detect these magnetic signals from ocean circulation using an observing system simulation experiment. The introduced approach relies on the assimilation of satellite magnetometer data based on a Kalman filter algorithm. The separation from other magnetic contributions is attained by predicting the temporal behavior of the ocean-induced magnetic field through presumed proxies. We evaluate the proposed method in different test case scenarios. The results demonstrate a possible detectability of the magnetic signal in large parts of the ocean. Furthermore, we point out the crucial dependence on the magnetic signal's variability and show that our approach is robust to slight spatial and temporal deviations of the presumed proxies. Additionally, we showed that including simple prior spatial constraints could further improve the assimilation results. Our findings indicate an appropriate sensitivity of the detection method for an application outside the presented observing system simulation experiment. Therefore, we finally discussed potential issues and required advances toward the method's application on original geomagnetic satellite observations.

Keywords: Electromagnetic induction, Ocean circulation, Satellite magnetometer observations, Kalman filter, Assimilation, Observing system simulation experiment



Graphical abstract

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FULL PAPER **Open Access**

Improving the estimation of thermospheric neutral density via two-step assimilation of in situ neutral density into a numerical model

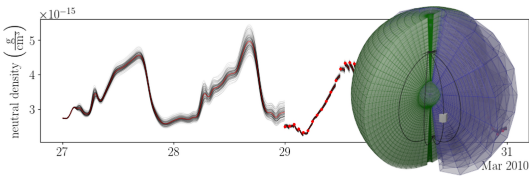
Armin Corbin* and Jürgen Kusche

Earth, Planets and Space 2022, **74**:183 DOI: 10.1186/s40623-022-01733-z
Received: 5 May 2022, Accepted: 3 November 2022, Published: 9 December 2022

Abstract

Neutral thermospheric density is an essential quantity required for precise orbit determination of satellites, collision avoidance of satellites, re-entry prediction of satellites or space debris, and satellite lifetime assessments. Empirical models of the thermosphere fail to provide sufficient estimates of neutral thermospheric density along the orbits of satellites by reason of approximations, assumptions and a limited temporal resolution. At high solar activity these estimates can be off by 70% when comparing to observations at 12-hourly averages. In recent decades, neutral density is regularly observed with satellite accelerometers on board of low Earth orbiting satellites like CHAMP, GOCE, GRACE, GRACE-FO, or Swarm. When assimilating such along-track information into global models of thermosphere–ionosphere dynamics, it has been often observed that only a very local sub-domain of the model grid around the satellite's position is updated. To extend the impact to the entire model domain we suggest a new two-step approach: we use accelerometer-derived neutral densities from the CHAMP mission in a first step to calibrate an empirical thermosphere density model (NRLMSIS 2.0). In a second step, we assimilate—for the first time—densities predicted for a regular three-dimensional grid into the TIE-GCM (Thermosphere Ionosphere Electrodynamics General Circulation Model). Data assimilation is performed using the Local Error-Subspace Transform Kalman Filter provided by the Parallel Data Assimilation Framework (PDAF). We test the new approach using a 2-week-long period containing the 5 April 2010 Geomagnetic storm. Accelerometer-derived neutral densities from the GRACE mission are used for additional evaluation. We demonstrate that the two-step approach globally improves the simulation of thermospheric density. We could significantly improve the density prediction for CHAMP and GRACE. In fact, the offset between the accelerometer-derived densities and the model prediction is reduced by 45% for CHAMP and 20% for GRACE when applying the two-step approach. The implication is that our approach allows one to much better 'transplant' the precise CHAMP thermospheric density measurements to satellites flying at a similar altitude.

Keywords: Thermosphere, Neutral mass density, Data assimilation, Geomagnetic storm



Graphical abstract

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FULL PAPER **Open Access**

Planetary-scale MLT waves diagnosed through multi-station methods: a review

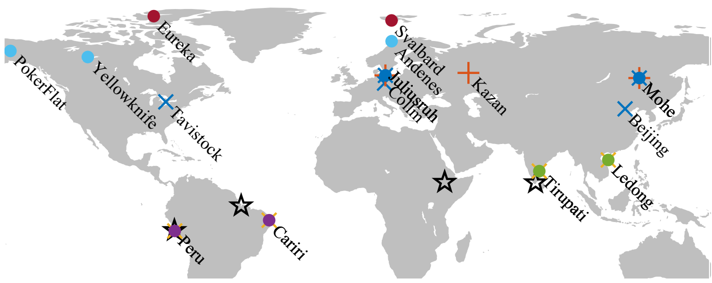
Maosheng He

Earth, Planets and Space 2023, **75**:63 DOI: 10.1186/s40623-023-01808-5
Received: 18 March 2022, Accepted: 21 March 2023, Published: 28 April 2023

Abstract

Most experimental investigations on planetary-scale waves in the mesosphere and lower thermosphere (MLT) region are based on single-station or -satellite spectral analysis methods, which suffer from intrinsic spectral aliasing/ambiguity. To overcome the aliasing, the author has developed and utilized dual- and multi-station spectral methods in a series of recent works. These methods were implemented on meteor radar observations and surface magnetometer observations. In the implements, a variety of waves were discovered or investigated in terms of seasonal variations and responses to sudden stratospheric warming events, such as lunar and solar tides (migrating and non-migrating), Rossby wave normal modes, ultra-fast Kelvin waves, and secondary waves of wave–wave nonlinear interactions between the previous waves. The current paper illustrates these methods using synthetic data, comparatively reviews the methods and results in plain language, and proposes a new representation, termed the adjusted Feynman diagram, to summarize the nonlinear interactions and explain their implications.

Keywords: Mesosphere and lower thermosphere (MLT) region, Solar and lunar tide, Planetary wave, Wave–wave nonlinear interaction, Adjusted Feynman diagram, Sudden stratospheric warming



Graphical abstract

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EXPRESS LETTER **Open Access**

Evidence for presence of a global quasi-resonant mode of oscillations during high-intensity long-duration continuous AE activity (HILDCAA) events

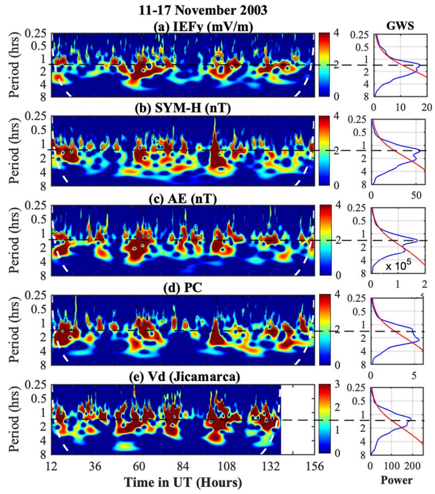
Diptiranjan Rout*, Ram Singh, K. Pandey, T. K. Pant, C. Stolle, D. Chakrabarty, S. Thampi and T. Bag

Earth, Planets and Space 2022, **74**:91 DOI: 10.1186/s40623-022-01642-1
Received: 5 January 2022, Accepted: 4 May 2022, Published: 13 June 2022

Abstract

The responses of two High-Intensity Long-Duration Continuous AE Activity (HILDCAA) events are investigated using solar wind observations at L1, magnetospheric measurements at geosynchronous orbit, and changes in the global ionosphere. This study provides evidence of the existence of quasi-periodic oscillations (1.5–2 h) in the ionospheric electric field over low latitudes, total electron content at high latitudes, the magnetic field over the globe, energetic electron flux and magnetic field at geosynchronous orbit, geomagnetic indices (SYM-H, AE, and PC) and the Y-component of the interplanetary electric field (IEFy) during the HILDCAA events at all local times. Based on detailed wavelet and cross-spectrum analyses, it is shown that the quasi-periodic oscillation of 1.5–2 h in IEFy is the most effective one that controls the solar wind–magnetosphere–ionosphere coupling process during the HILDCAA events for several days. Therefore, this investigation for the first time, shows that the HILDCAA event affects the global magnetosphere–ionosphere system with a "quasi-resonant" mode of oscillation.

Keywords: HILDCAA, CIR, Prompt penetration electric field, Global oscillation, Magnetosphere–ionosphere coupling



Graphical abstract

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TECHNICAL REPORT **Open Access**

Geomagnetic data from the GOCE satellite mission

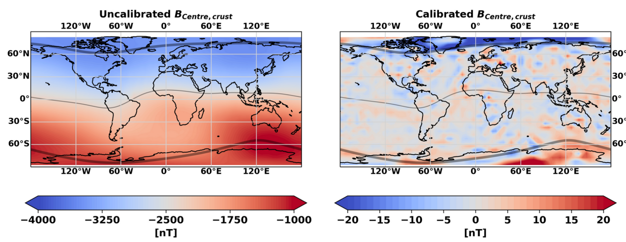
I. Michaelis*, K. Styp-Rekowski, J. Rauberg, C. Stolle and M. Korte

Earth, Planets and Space 2022, **74**:135 DOI: 10.1186/s40623-022-01691-6
Received: 8 April 2022, Accepted: 13 August 2022, Published: 13 September 2022

Abstract

The Gravity field and steady-state Ocean Circulation Explorer (GOCE) is part of ESA's Earth Explorer Program. The satellite carries magnetometers that control the activity of magnetorquers for navigation of the satellite, but are not dedicated as science instruments. However, intrinsic steady states of the instruments can be corrected by alignment and calibration, and artificial perturbations, e.g. from currents, can be removed by their characterisation correlated to housekeeping data. The leftover field then shows the natural evolution and variability of the Earth's magnetic field. This article describes the pre-processing of input data as well as calibration and characterisation steps performed on GOCE magnetic data, using a high-precision magnetic field model as reference. For geomagnetic quiet times, the standard deviation of the residual is below 13 nT with a median residual of (11.7, 9.6, 10.4) nT for the three magnetic field components (x, y, z). For validation of the calibration and characterisation performance, we selected a geomagnetic storm event in March 2013. GOCE magnetic field data show good agreement with results from a ground magnetic observation network. The GOCE mission overlaps with the dedicated magnetic field satellite mission CHAMP for a short time at the beginning of 2010, but does not overlap with the Swarm mission or any other mission flying at low altitude and carrying high-precision magnetometers. We expect calibrated GOCE magnetic field data to be useful for lithospheric modelling and filling the gap between the dedicated geomagnetic missions CHAMP and Swarm.

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



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A Grant-in-Aid for Publication of Scientific Research Results (19HP1001) from Japan Society for the Promotion of Science is used for printing.

Contents

Cover image: Rodríguez-Zuluaga, J. *et al.*, *Earth, Planets and Space* 2022, **74**:119 DOI: 10.1186/s40623-022-01679-2