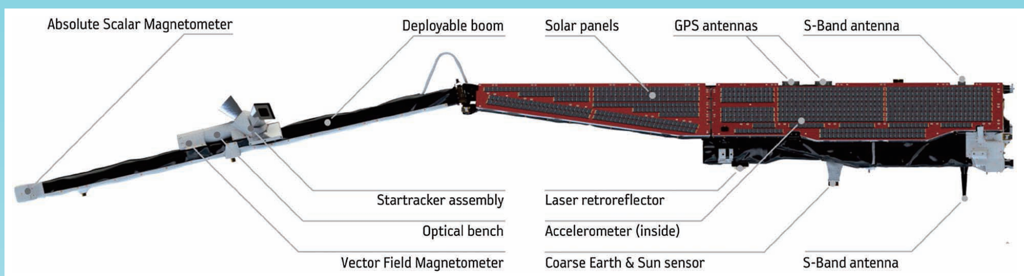
Earth, Planets and Space

Swarm Science Results after Two Years in Space



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PREFACE

Open Access

Special issue "Swarm science results after 2 years in space"

Nils Olsen[1*], Claudia Stolle[2], Rune Floberghagen[3], Gauthier Hulot[4] and Alexey Kuvshinov[5]

Swarm is a three-satellite constellation mission launched by the European Space Agency (ESA) on 22 November 2013. It consists of three identical spacecraft, two of which (*Swarm Alpha* and *Swarm Charlie*) are flying almost side-by-side in polar orbits at lower altitude (about 470 km in September 2016) with an East-West separation of 1.4° in longitude corresponding to 155 km at the equator. The third satellite (*Swarm Bravo*) is in a slightly higher orbit (about 520 km altitude in September 2016). Each of the three satellites carry a magnetometry package (consisting of absolute scalar magnetometer, fluxgate vector magnetometer, and star imager) for measuring the direction and strength of the magnetic field, and instruments to measure plasma and electric field parameters as well as gravitational acceleration. Time and position are provided by on-board GPS. The configuration of the various instruments on each of the three *Swarm* spacecraft is shown in Fig. 1. More information about the mission can be found at http://earth.esa.int/swarm.

The 21 articles collected in this special issue were stimulated by the Joint Inter-Association Symposium "JA4 Results from Swarm, Ground Based Data and Earlier Satellite Missions" at the 26th General Assembly of the International Union of Geodesy and Geophysics (IUGG) held in Prague in July 2015.

Tøffner-Clausen et al. (2016) report on the advanced calibration of the magnetometry package of the *Swarm* satellites. Finlay et al. (2016) and Olsen et al. (2016) present models of Earth's core magnetic field, while Thébault et al. (2016) and Kotsiaros (2016) determine models of the lithospheric field. The importance of high-resolution magnetic field models for studying external magnetic field contributions, in particular during geomagnetic quiet conditions, is discussed by Stolle et al. (2016).

Five contributions discuss the magnetic field produced by ionospheric and magnetospheric currents: Chulliat et al. (2016) present a climatological model of the ionospheric currents responsible for geomagnetic daily variations at non-polar latitudes, while the work of Laundal et al. (2016) concentrates on a consistent description of horizontal ionospheric and field-aligned currents in the polar ionosphere, in particular regarding their dependence on solar irradiation that controls ionospheric conductivity. A scheme for estimating the polar ionospheric currents that form the Polar Electrojets on an orbit-by-orbit basis is presented by Aakjær et al. (2016), while Tozzi et al. (2016) discuss unmodelled magnetic field contributions in satellite-based magnetic field models. Michelis et al. (2016) present a study of high-latitude magnetic field variations during the St. Patrick's Day Storm.

The same event is investigated by Pignalberi et al. (2016) using *Swarm* plasma density measurements, and by Cherniak and Zakharenkova (2016) using GPS data from ground and *Swarm*.

Calibration of the electric field instrument of *Swarm* is presented by Fiori et al. (2016). A combination of electric, magnetic, and TEC observations has been used by Astafyeva et al. (2016) to investigate the magnetic storm of 22–23 June 2015. Aoyama et al. (2016) combine ground magnetic data and *Swarm* TEC observations to study possible ionospheric effects of the 2015 eruption of a volcano in Chile, Zakharenkova et al. (2016) used GPS and *Swarm* plasma observations to study equatorial plasma density irregularities in the topside ionosphere, and Xiong et al. (2016) performed a scale analysis of equatorial plasma irregularities.

van den IJssel et al. (2016) describe improvements of *Swarm* GPS antenna settings to enhance high-precision positioning of the spacecraft, and da Encarnação et al. (2016) discuss various attempts to determine monthly

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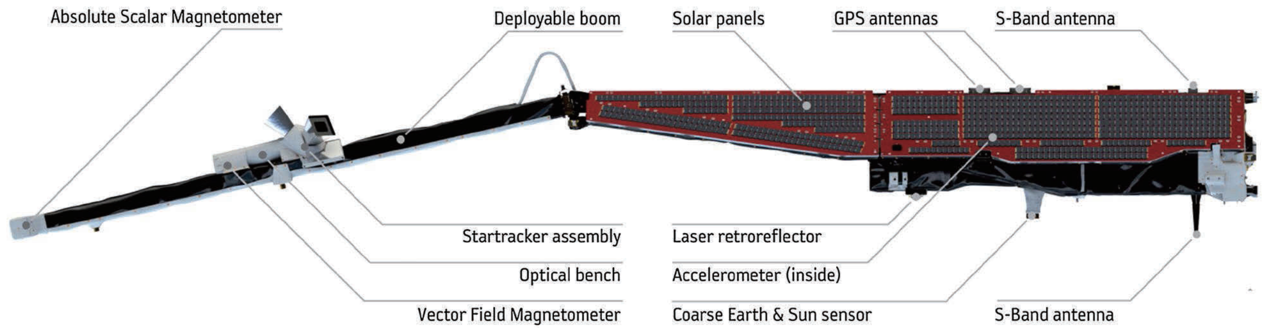

Fig. 1 Various scientific instruments on board each of the three *Swarm* satellites (ESA/AOES Medialab)

snapshot models of the large-scale part of Earth's gravity field from *Swarm* GPS observations.

Finally, the processing of the *Swarm* accelerometer data is described by Siemes et al. (2016).

The work reported in this issue could not have been achieved without the unfailing support of our deeply regretted friend and colleague Gernot Plank (Fig. 2), to which we wish to dedicate this special issue of *Earth Planets Space*. Gernot has been one of the major contributors to the success of the *Swarm* mission. With great enthusiasm he played a considerable role in the establishment of *Swarm SCARF*, the *Swarm* Level-2 data processing facility. *Swarm SCARF* was key to the project and all scientific results presented in the present special issue (as well an in a previous issue, see *Earth Planets Space*, Vol. 65, Issue 11) heavily rely on the success of this facility. Gernot's energy and enthusiastic spirit, from beginning to end of even the most intense meetings, was extremely appreciated. He had a remarkable ability to help solve problems and convince anyone to do the right thing in the interest of the project and science, sometimes even very late in the evening, and always in his unique and particularly cheerful way, whatever the circumstances.

Fig. 2 Gernot Plank (1967–2016)

Gernot passed away in March 2016 after a lengthy, hard, and unfair fight against cancer. He, and his legendary laugh, will be sorrowfully missed by his friends and colleagues.

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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FRONTIER LETTER **Open Access**

In-flight scalar calibration and characterisation of the Swarm magnetometry package

Lars Tøffner-Clausen*, Vincent Lesur, Nils Olsen and Christopher C. Finlay

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Abstract

We present the in-flight scalar calibration and characterisation of the *Swarm* magnetometry package consisting of the absolute scalar magnetometer, the vector magnetometer, and the spacecraft structure supporting the instruments. A significant improvement in the scalar residuals between the pairs of magnetometers is demonstrated, confirming the high performance of these instruments. The results presented here, including the characterisation of a Sun-driven disturbance field, form the basis of the correction of the magnetic vector measurements from *Swarm* which is applied to the *Swarm* Level 1b magnetic data.

Keywords: Geomagnetism; Magnetometer; Instrument calibration; Satellite; *Swarm*

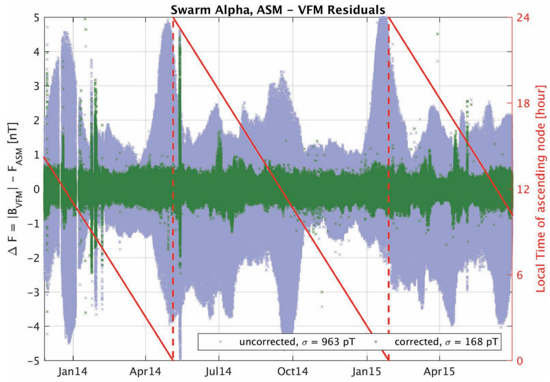

Figure 1

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FULL PAPER **Open Access**

Impact of Swarm GPS receiver updates on POD performance

Jose van den IJssel*, Biagio Forte and Oliver Montenbruck

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Abstract

The Swarm satellites are equipped with state-of-the-art Global Positioning System (GPS) receivers, which are used for the precise geolocation of the magnetic and electric field instruments, as well as for the determination of the Earth's gravity field, the total electron content and low-frequency thermospheric neutral densities. The onboard GPS receivers deliver high-quality data with an almost continuous data rate. However, the receivers show a slightly degraded performance when flying over the geomagnetic poles and the geomagnetic equator, due to ionospheric scintillation. Furthermore, with only eight channels available for dual-frequency tracking, the amount of collected GPS tracking data is relatively low compared with various other missions. Therefore, several modifications have been implemented to the Swarm GPS receivers. To optimise the amount of collected GPS data, the GPS antenna elevation mask has slowly been reduced from 10° to 2°. To improve the robustness against ionospheric scintillation, the bandwidths of the GPS receiver tracking loops have been widened. Because these modifications were first implemented on Swarm-C, their impact can be assessed by a comparison with the close flying Swarm-A satellite. This shows that both modifications have a positive impact on the GPS receiver performance. The reduced elevation mask increases the amount of GPS tracking data by more than 3 %, while the updated tracking loops lead to around 1.3 % more observations and a significant reduction in tracking losses due to severe equatorial scintillation. The additional observations at low elevation angles increase the average noise of the carrier phase observations, but nonetheless slightly improve the resulting reduced-dynamic and kinematic orbit accuracy as shown by independent satellite laser ranging (SLR) validation. The more robust tracking loops significantly reduce the large carrier phase observation errors at the geomagnetic poles and along the geomagnetic equator and do not degrade the observations at midlatitudes. SLR validation indicates that the updated tracking loops also improve the reduced-dynamic and kinematic orbit accuracy. It is expected that the Swarm gravity field recovery will benefit from the improved kinematic orbit quality and potentially also from the expected improvement of the kinematic baseline determination and the anticipated reduction in the systematic gravity field errors along the geomagnetic equator. Finally, other satellites that carry GPS receivers that encounter similar disturbances might also benefit from this analysis.

Keywords: Swarm; GPS; Precise orbit determination; Ionospheric scintillation; Elevation mask; Tracking loop

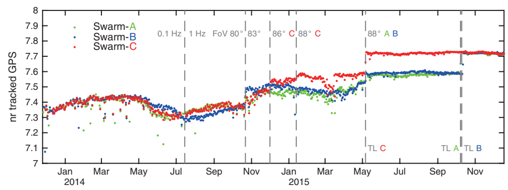

Figure 1

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Swarm accelerometer data processing from raw accelerations to thermospheric neutral densities

Christian Siemes*, João de Teixeira da Encarnação, Eelco Doornbos, Jose van den IJssel, Jiří Kraus, Radek Peřeštý, Ludwig Grunwaldt, Guy Apelbaum, Jakob Flury and Poul Erik Holmdahl Olsen

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Abstract

The Swarm satellites were launched on November 22, 2013, and carry accelerometers and GPS receivers as part of their scientific payload. The GPS receivers do not only provide the position and time for the magnetic field measurements, but are also used for determining non-gravitational forces like drag and radiation pressure acting on the spacecraft. The accelerometers measure these forces directly, at much finer resolution than the GPS receivers, from which thermospheric neutral densities can be derived. Unfortunately, the acceleration measurements suffer from a variety of disturbances, the most prominent being slow temperature-induced bias variations and sudden bias changes. In this paper, we describe the new, improved four-stage processing that is applied for transforming the disturbed acceleration measurements into scientifically valuable thermospheric neutral densities. In the first stage, the sudden bias changes in the acceleration measurements are manually removed using a dedicated software tool. The second stage is the calibration of the accelerometer measurements against the non-gravitational accelerations derived from the GPS receiver, which includes the correction for the slow temperature-induced bias variations. The identification of validity periods for calibration and correction parameters is part of the second stage. In the third stage, the calibrated and corrected accelerations are merged with the non-gravitational accelerations derived from the observations of the GPS receiver by a weighted average in the spectral domain, where the weights depend on the frequency. The fourth stage consists of transforming the corrected and calibrated accelerations into thermospheric neutral densities. We present the first results of the processing of Swarm C acceleration measurements from June 2014 to May 2015. We started with Swarm C because its acceleration measurements contain much less disturbances than those of Swarm A and have a higher signal-to-noise ratio than those of Swarm B. The latter is caused by the higher altitude of Swarm B as well as larger noise in the acceleration measurements of Swarm B. We show the results of each processing stage, highlight the difficulties encountered, and comment on the quality of the thermospheric neutral density data set.

Keywords: Swarm mission; Accelerometry; Thermospheric neutral density; Non-gravitational accelerations

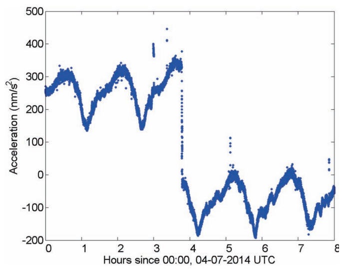

Figure 1

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Comparison between IRI and preliminary Swarm Langmuir probe measurements during the St. Patrick storm period

Alessio Pignalberi, Michael Pezzopane*, Roberta Tozzi, Paola De Michelis and Igino Coco

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Abstract

Preliminary Swarm Langmuir probe measurements recorded during March 2015, a period of time including the St. Patrick storm, are considered. Specifically, six time periods are identified: two quiet periods before the onset of the storm, two periods including the main phase of the storm, and two periods during the recovery phase of the storm. Swarm electron density values are then compared with the corresponding output given by the International Reference Ionosphere (IRI) model, according to its three different options for modelling the topside ionosphere. Since the Swarm electron density measurements are still undergoing a thorough validation, a comparison with IRI in terms of absolute values would have not been appropriate. Hence, the similarity of trends embedded in the Swarm and IRI time series is investigated in terms of Pearson correlation coefficient. The analysis shows that the electron density representations made by Swarm and IRI are different for both quiet and disturbed periods, independently of the chosen topside model option. Main differences between trends modelled by IRI and those observed by Swarm emerge, especially at equatorial latitudes, and at northern high latitudes, during the main and recovery phases of the storm. Moreover, very low values of electron density, even lower than 2×10^4 cm^{-3}, were simultaneously recorded in the evening sector by Swarm satellites at equatorial latitudes during quiet periods, and at magnetic latitudes of about ±60° during disturbed periods. The obtained results are an example of the capability of Swarm data to generate an additional valuable dataset to properly model the topside ionosphere.

Keywords: IRI model; Swarm data; Topside electron density; St. Patrick storm

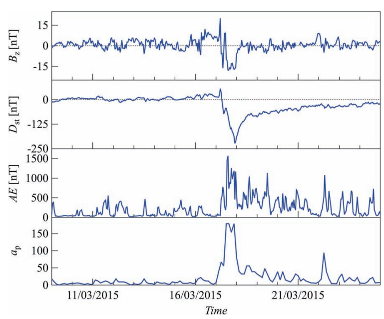

Figure 1

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Calibration and assessment of Swarm ion drift measurements using a comparison with a statistical convection model

R. A. D. Fiori*, A. V. Koustov, D. H. Boteler, D. J. Knudsen and J. K. Burchill

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Abstract

The electric field instruments onboard the Swarm satellites make high-resolution measurements of the F-region ion drift. This paper presents an initial investigation of preliminary ion drift data made available by the European Space Agency. Based on data taken during polar cap crossings, we identify large offsets in both the along-track and cross-track components of the measured ion drift. These offsets are removed by zeroing drift values at the low-latitude boundary of the high-latitude convection pattern. This correction is shown to significantly improve agreement between the Swarm ion drift measurements and velocity inferred from a radar-based statistical convection model for periods of quasi-stability in the solar wind and interplanetary magnetic field. Agreement is most pronounced in the cross-track direction ($R = 0.60$); it improves slightly ($R = 0.63$) if data are limited to periods with IMF $B_z < 0$. The corrected Swarm data were shown to properly identify the convection reversal boundary for periods of IMF $B_z < 0$, in full agreement with previous radar and satellite measurements, making Swarm ion drift measurements a valuable input for ionospheric modeling.

Keywords: Ion drift; Swarm electric field instrument; Ionospheric plasma flow

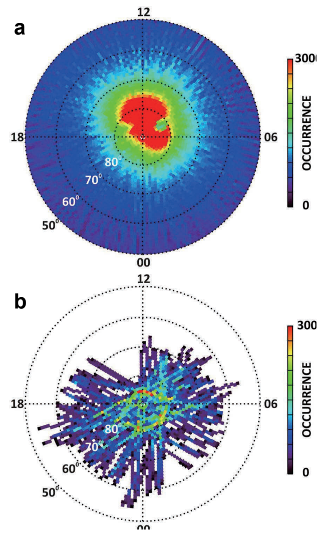

Figure 1

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FULL PAPER Open Access

First results from the Swarm Dedicated Ionospheric Field Inversion chain

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Abstract

Data-based modeling of the magnetic field originating in the Earth's ionosphere is challenging due to the multiple timescales involved and the small spatial scales of some of the current systems, especially the equatorial electrojet (EEJ) that flows along the magnetic dip equator. The Dedicated Ionospheric Field Inversion (DIFI) algorithm inverts a combination of Swarm satellite and ground observatory data at mid- to low latitudes and provides models of the solar-quiet (Sq) and EEJ magnetic fields on the ground and at satellite altitude. The basis functions of these models are spherical harmonics in quasi-dipole coordinates and Fourier series describing the 24-, 12-, 8- and 6-h periodicities, as well as the annual and semiannual variations. A 1-D conductivity model of the Earth and a 2-D conductivity model of the oceans and continents are used to separate the primary ionospheric field from its induced counterpart. First results from the DIFI algorithm confirm several well-known features of the seasonal variability and westward drift speed of the Sq current systems. They also reveal a peculiar seasonal variability of the Sq field in the Southern hemisphere and a longitudinal variability reminiscent of the EEJ wave-4 structure in the same hemisphere. These observations suggest that the Sq and EEJ currents might be electrically coupled, but only for some seasons and longitudes and more so in the Southern hemisphere than in the Northern hemisphere.

Keywords: Swarm; Geomagnetism; Ionosphere; Sq; Equatorial electrojet

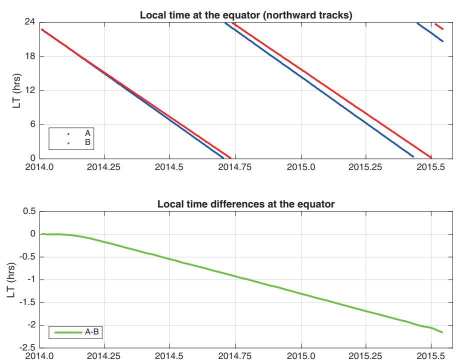

Figure 1

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Observations of high-latitude geomagnetic field fluctuations during St. Patrick's Day storm: Swarm and SuperDARN measurements

Paola De Michelis*, Giuseppe Consolini, Roberta Tozzi and Maria Federica Marcucci

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Abstract

The aim of this work is to study the properties of the magnetic field's fluctuations produced by ionospheric and magnetospheric electric currents during the St. Patrick's Day geomagnetic storm (17 March 2015). We analyse the scaling features of the external contribution to the horizontal geomagnetic field recorded simultaneously by the three satellites of the Swarm constellation during a period of 13 days (13–25 March 2015). We examine the different latitudinal structure of the geomagnetic field fluctuations and analyse the dynamical changes in the magnetic field scaling features during the development of the geomagnetic storm. Analysis reveals consistent patterns in the scaling properties of magnetic fluctuations and striking changes between the situation before the storm, during the main phase and recovery phase. We discuss these dynamical changes in relation to those of the overall ionospheric polar convection and potential structures as reconstructed using SuperDARN data. Our findings suggest that distinct turbulent regimes characterised the mesoscale magnetic field's fluctuations and that some factors, which are known to influence large-scale fluctuations, have also an influence on mesoscale fluctuations. The obtained results are an example of the capability of geomagnetic field fluctuations data to provide new insights about ionospheric dynamics and ionosphere–magnetosphere coupling. At the same time, these results could open doors for development of new applications where the dynamical changes in the scaling features of the magnetic fluctuations are used as local indicators of magnetospheric conditions.

Keywords: High-latitude phenomena; Solar wind–magnetosphere interactions; Ionospheric turbulence; Swarm magnetic measurements

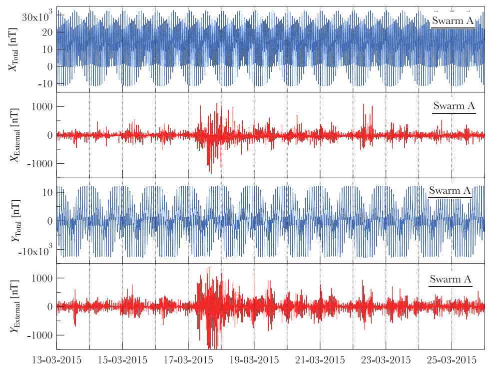

Figure 1

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Unmodelled magnetic contributions in satellite-based models

Roberta Tozzi*, Mioara Mandea and Paola De Michelis

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Abstract

A complex system of electric currents flowing in the ionosphere and magnetosphere originates from the interaction of the solar wind and the Interplanetary Magnetic Field (IMF) with the Earth's magnetic field. These electric currents generate magnetic fields contributing themselves to those measured by both ground observatories and satellites. Here, low-resolution (1 Hz) magnetic vector data recorded between 1 March 2014 and 31 May 2015 by the recently launched Swarm constellation are considered. The core and crustal magnetic fields and part of that originating in the magnetosphere are removed from Swarm measurements using CHAOS-5 model. Low- and mid-latitude residuals of the geomagnetic field representing the ionospheric and the unmodelled magnetospheric contributions are investigated, in the Solar Magnetic frame, according to the polarity of IMF B_y (azimuthal) and B_z (north–south) components and to different geomagnetic activity levels. The proposed approach makes it possible to investigate the features of unmodelled contributions due to the external sources of the geomagnetic field. Results show, on one side, the existence of a relation between the analysed residuals and IMF components B_y and B_z, possibly due to the long distance effect of high-latitude field-aligned currents. On the other side, they suggest the presence of a contribution due to the partial ring current that is activated during the main phase of geomagnetic storms. The perturbation observed on residuals is also compatible with the effect of the net field-aligned currents. Moreover, we have quantitatively estimated the effect of these current systems on computed residuals.

Keywords: Swarm magnetic vector data; Interplanetary Magnetic Field; Magnetic models; Field-aligned currents; Partial ring current

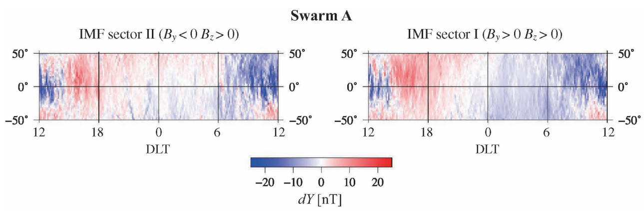

Figure 1

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FULL PAPER Open Access

Recent geomagnetic secular variation from *Swarm* and ground observatories as estimated in the CHAOS-6 geomagnetic field model

Christopher C. Finlay*, Nils Olsen, Stavros Kotsiaros, Nicolas Gillet and Lars Tøffner-Clausen

Earth, Planets and Space 2016, **68**:112 DOI: 10.1186/s40623-016-0486-1
Received: 31 December 2015, Accepted: 9 June 2016, Published: 11 July 2016

Abstract

We use more than 2 years of magnetic data from the *Swarm* mission, and monthly means from 160 ground observatories as available in March 2016, to update the CHAOS time-dependent geomagnetic field model. The new model, CHAOS-6, provides information on time variations of the core-generated part of the Earth's magnetic field between 1999.0 and 2016.5. We present details of the secular variation (SV) and secular acceleration (SA) from CHAOS-6 at Earth's surface and downward continued to the core surface. At Earth's surface, we find evidence for positive acceleration of the field intensity in 2015 over a broad area around longitude 90°E that is also seen at ground observatories such as Novosibirsk. At the core surface, we are able to map the SV up to at least degree 16. The radial field SA at the core surface in 2015 is found to be largest at low latitudes under the India–South-East Asia region, under the region of northern South America, and at high northern latitudes under Alaska and Siberia. Surprisingly, there is also evidence for significant SA in the central Pacific region, for example near Hawaii where radial field SA is observed on either side of a jerk in 2014. On the other hand, little SV or SA has occurred over the past 17 years in the southern polar region. Inverting for a quasi-geostrophic core flow that accounts for this SV, we obtain a prominent planetary-scale, anti-cyclonic, gyre centred on the Atlantic hemisphere. We also find oscillations of non-axisymmetric, azimuthal, jets at low latitudes, for example close to 40°W, that may be responsible for localized SA oscillations. In addition to scalar data from Ørsted, CHAMP, SAC-C and *Swarm*, and vector data from Ørsted, CHAMP and *Swarm*, CHAOS-6 benefits from the inclusion of along-track differences of scalar and vector field data from both CHAMP and the three *Swarm* satellites, as well as east–west differences between the lower pair of *Swarm* satellites, *Alpha* and *Charlie*. Moreover, ground observatory SV estimates are fit to a Huber-weighted rms level of 3.1 nT/year for the eastward components and 3.8 and 3.7 nT/year for the vertical and southward components. We also present an update of the CHAOS high-degree lithospheric field, making use of along-track differences of CHAMP scalar and vector field data to produce a new static field model that agrees well with the MF7 field model out to degree 110.

Keywords: Geomagnetism; Secular variation; Field modelling; Core dynamics; *Swarm*

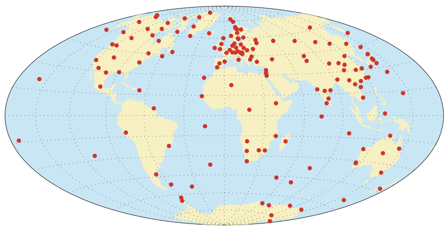

Figure 1

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FULL PAPER Open Access

Scale analysis of equatorial plasma irregularities derived from Swarm constellation

Chao Xiong*, Claudia Stolle, Hermann Lühr, Jaeheung Park, Bela G. Fejer and Guram N. Kervalishvili

Earth, Planets and Space 2016, **68**:121 DOI: 10.1186/s40623-016-0502-5
Received: 11 December 2015, Accepted: 28 June 2016, Published: 15 July 2016

Abstract

In this study, we investigated the scale sizes of equatorial plasma irregularities (EPIs) using measurements from the Swarm satellites during its early mission and final constellation phases. We found that with longitudinal separation between Swarm satellites larger than 0.4°, no significant correlation was found any more. This result suggests that EPI structures include plasma density scale sizes less than 44 km in the zonal direction. During the Swarm earlier mission phase, clearly better EPI correlations are obtained in the northern hemisphere, implying more fragmented irregularities in the southern hemisphere where the ambient magnetic field is low. The previously reported inverted-C shell structure of EPIs is generally confirmed by the Swarm observations in the northern hemisphere, but with various tilt angles. From the Swarm spacecrafts with zonal separations of about 150 km, we conclude that larger zonal scale sizes of irregularities exist during the early evening hours (around 1900 LT).

Keywords: Equatorial plasma irregularities; Ionospheric scale lengths; Swarm constellation

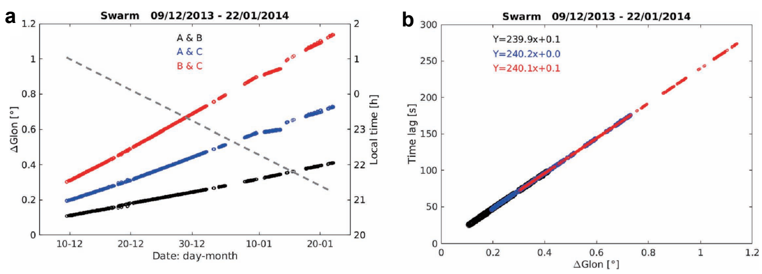

Figure 1

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FULL PAPER Open Access

Gravity field models derived from Swarm GPS data

João Teixeira da Encarnação*, Daniel Arnold, Aleš Bezděk, Christoph Dahle, Eelco Doornbos, Jose van den IJssel, Adrian Jäggi, Torsten Mayer-Gürr, Josef Sebera, Pieter Visser and Norbert Zehentner

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Abstract

It is of great interest to numerous geophysical studies that the time series of global gravity field models derived from Gravity Recovery and Climate Experiment (GRACE) data remains uninterrupted after the end of this mission. With this in mind, some institutes have been spending efforts to estimate gravity field models from alternative sources of gravimetric data. This study focuses on the gravity field solutions estimated from Swarm global positioning system (GPS) data, produced by the Astronomical Institute of the University of Bern, the Astronomical Institute (ASU, Czech Academy of Sciences) and Institute of Geodesy (IfG, Graz University of Technology). The three sets of solutions are based on different approaches, namely the celestial mechanics approach, the acceleration approach and the short-arc approach, respectively. We derive the maximum spatial resolution of the time-varying gravity signal in the Swarm gravity field models to be degree 12, in comparison with the more accurate models obtained from K-band ranging data of GRACE. We demonstrate that the combination of the GPS-driven models produced with the three different approaches improves the accuracy in all analysed monthly solutions, with respect to any of them. In other words, the combined gravity field model consistently benefits from the individual strengths of each separate solution. The improved accuracy of the combined model is expected to bring benefits to the geophysical studies during the period when no dedicated gravimetric mission is operational.

Keywords: Gravity field; Swarm; High–low satellite-to-satellite tracking; GRACE

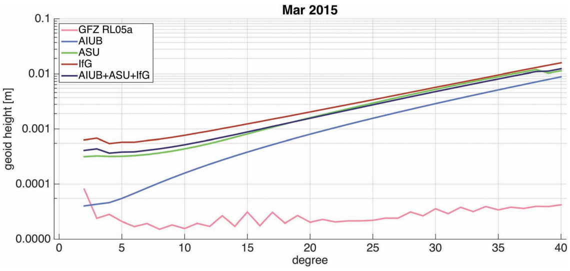

Figure 1

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FULL PAPER Open Access

Toward more complete magnetic gradiometry with the Swarm mission

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Abstract

An analytical and numerical analysis of the spectral properties of the gradient tensor, initially performed by Rummel and van Gelderen (Geophys J Int 111(1):159–169, 1992) for the gravity potential, shows that when the tensor elements are grouped into sets of semi-tangential and pure-tangential parts, they produce almost identical signal content as the normal element. Moreover, simple eigenvalue relations can be derived between these sets and the spherical harmonic expansion of the potential. This theoretical development generally applies to any potential field. First, the analysis of Rummel and van Gelderen (1992) is adapted to the magnetic field case and then the elements of the magnetic gradient tensor are estimated by 2 years of Swarm data and grouped into $\Gamma^{(1)}=\{[\nabla\mathbf{B}]_{r\theta}, [\nabla\mathbf{B}]_{r\varphi}\}$ resp. $\Gamma^{(2)}=\{[\nabla\mathbf{B}]_{\theta\theta}-[\nabla\mathbf{B}]_{\varphi\varphi}, 2[\nabla\mathbf{B}]_{\theta\varphi}\}$. It is shown that the estimated combinations $\Gamma^{(1)}$ and $\Gamma^{(2)}$ produce similar signal content as the theoretical radial gradient $\Gamma^{(0)}=\{[\nabla\mathbf{B}]_{rr}\}$. These results demonstrate the ability of multi-satellite missions such as Swarm, which cannot directly measure the radial gradient, to retrieve similar signal content by means of the horizontal gradients. Finally, lithospheric field models are derived using the gradient combinations $\Gamma^{(1)}$ and $\Gamma^{(2)}$ and compared with models derived from traditional vector and gradient data. The model resulting from $\Gamma^{(1)}$ leads to a very similar, and in particular cases improved, model compared to models retrieved by using approximately three times more data, i.e., a full set of vector, North–South and East–West gradients. This demonstrates the high information content of $\Gamma^{(1)}$.

Keywords: Crustal field; Swarm gradients; Field modeling

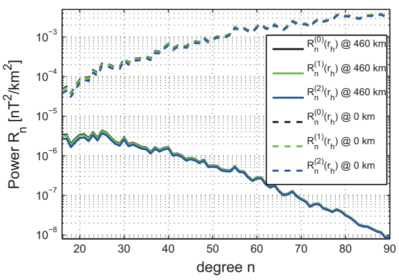

Figure 1

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FULL PAPER Open Access

Determining polar ionospheric electrojet currents from *Swarm* satellite constellation magnetic data

Cecilie Drost Aakjær*, Nils Olsen and Christopher C. Finlay

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Received: 8 February 2016, Accepted: 6 July 2016, Published: 5 August 2016

Abstract

We determine the strength and location of the ionospheric currents responsible for the polar electrojets from magnetic data collected by the *Swarm* satellite constellation on an orbit-by-orbit basis. The ionospheric currents are modelled using a simple, yet robust, method by a series of line currents at 110 km altitude (corresponding to the ionospheric E-layer) perpendicular to the satellite orbit, separated by 1° (about 113 km). We assess the reliability of our method, with the aim of a possible near-real-time application. A study of the effect of different regularization methods is therefore carried out. An L_1 model regularization of the second-order spatial differences, and robust treatment of the data (to account for non-Gaussian error distributions), yields the most encouraging results. We apply our approach to two three-weekly data periods in March 2014 (geomagnetic quiet conditions) and March 2015 (more disturbed conditions), respectively. Our orbit-by-orbit approach also allows the temporal evolution of the polar electrojets to be investigated. We find remarkable agreement of the ionospheric activity in Northern and Southern polar regions, with correlation exceeding 0.9 for periods longer than two days. Reliability of the approach is shown by three key results: (1) a common regularization parameter for all orbits with enough data coverage, (2) 0.95 squared coherence with the Auroral Electrojet index, and (3) 0.97 squared coherence is found between the side-by-side flying satellites, Alpha and Charlie, indicating a method invariant to small changes in data input. All these results indicate a possible automated near-real-time application.

Keywords: Geomagnetism; Field modelling; Ionosphere; *Swarm*

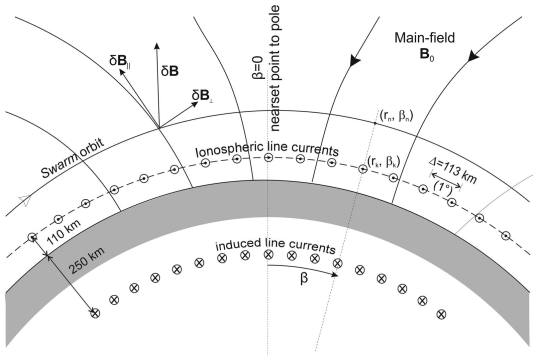

Figure 1

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FULL PAPER Open Access

Sunlight effects on the 3D polar current system determined from low Earth orbit measurements

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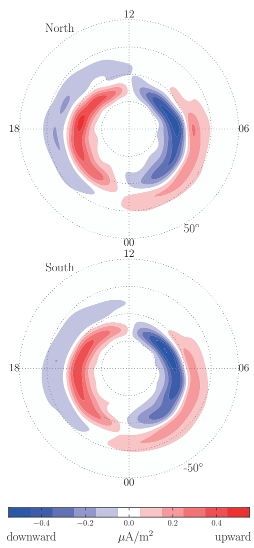
Abstract

Interaction between the solar wind and the Earth's magnetosphere is associated with large-scale currents in the ionosphere at polar latitudes that flow along magnetic field lines (Birkeland currents) and horizontally. These current systems are tightly linked, but their global behaviors are rarely analyzed together. In this paper, we present estimates of the average global Birkeland currents and horizontal ionospheric currents from the same set of magnetic field measurements. The magnetic field measurements, from the low Earth orbiting *Swarm* and CHAMP satellites, are used to co-estimate poloidal and toroidal parts of the magnetic disturbance field, represented in magnetic apex coordinates. The use of apex coordinates reduces effects of longitudinal and hemispheric variations in the Earth's main field. We present global currents from both hemispheres during different sunlight conditions. The results show that the Birkeland currents vary with the conductivity, which depends most strongly on solar EUV emissions on the dayside and on particle precipitation at pre-midnight magnetic local times. In sunlight, the horizontal equivalent current flows in two cells, resembling an opposite ionospheric convection pattern, which implies that it is dominated by Hall currents. By combining the Birkeland current maps and the equivalent current, we are able to calculate the total horizontal current, without any assumptions about the conductivity. We show that the total horizontal current is close to zero in the polar cap when it is dark. That implies that the equivalent current, which is sensed by ground magnetometers, is largely canceled by the horizontal closure of the Birkeland currents.



Keywords: Polar ionospheric currents; Birkeland currents; Equivalent currents; Apex coordinates; LEO magnetic field

Figure 1

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LETTER Open Access

The role of high-resolution geomagnetic field models for investigating ionospheric currents at low Earth orbit satellites

Claudia Stolle*, Ingo Michaelis and Jan Rauberg

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Received: 27 January 2016, Accepted: 15 June 2016, Published: 8 July 2016

Abstract

Low Earth orbiting geomagnetic satellite missions, such as the Swarm satellite mission, are the only means to monitor and investigate ionospheric currents on a global scale and to make in situ measurements of F region currents. High-precision geomagnetic satellite missions are also able to detect ionospheric currents during quiet-time geomagnetic conditions that only have few nanotesla amplitudes in the magnetic field. An efficient method to isolate the ionospheric signals from satellite magnetic field measurements has been the use of residuals between the observations and predictions from empirical geomagnetic models for other geomagnetic sources, such as the core and lithospheric field or signals from the quiet-time magnetospheric currents. This study aims at highlighting the importance of high-resolution magnetic field models that are able to predict the lithospheric field and that consider the quiet-time magnetosphere for reliably isolating signatures from ionospheric currents during geomagnetically quiet times. The effects on the detection of ionospheric currents arising from neglecting the lithospheric and magnetospheric sources are discussed on the example of four Swarm orbits during very quiet times. The respective orbits show a broad range of typical scenarios, such as strong and weak ionospheric signal (during day- and nighttime, respectively) superimposed over strong and weak lithospheric signals. If predictions from the lithosphere or magnetosphere are not properly considered, the amplitude of the ionospheric currents, such as the midlatitude Sq currents or the equatorial electrojet (EEJ), is modulated by 10–15 % in the examples shown. An analysis from several orbits above the African sector, where the lithospheric field is significant, showed that the peak value of the signatures of the EEJ is in error by 5 % in average when lithospheric contributions are not considered, which is in the range of uncertainties of present empirical models of the EEJ.

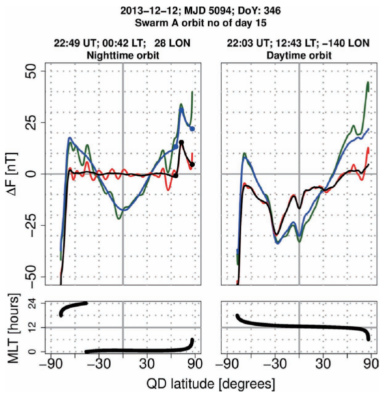

Figure 1

Keywords: Geomagnetic field; Ionospheric current; Geomagnetic models

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LETTER Open Access

GPS and in situ Swarm observations of the equatorial plasma density irregularities in the topside ionosphere

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Received: 31 December 2015, Accepted: 14 June 2016, Published: 15 July 2016

Abstract

Here we study the global distribution of the plasma density irregularities in the topside ionosphere by using the concurrent GPS and Langmuir probe measurements onboard the Swarm satellites. We analyze 18 months (from August 2014 till January 2016) of data from Swarm A and B satellites that flew at 460 and 510 km altitude, respectively. To identify the occurrence of the ionospheric irregularities, we have analyzed behavior of two indices ROTI and RODI based on the change rate of total electron content and electron density, respectively. The obtained results demonstrate a high degree of similarities in the occurrence pattern of the seasonal and longitudinal distribution of the topside ionospheric irregularities derived from both types of the satellite observations. Among the seasons with good data coverage, the maximal occurrence rates for the post-sunset equatorial irregularities reached 35–50 % for the September 2014 and March 2015 equinoxes and only 10–15 % for the June 2015 solstice. For the equinox seasons the intense plasma density irregularities were more frequently observed in the Atlantic sector, for the December solstice in the South American–Atlantic sector. The highest occurrence rates for the post-midnight irregularities were observed in African longitudinal sector during the September 2014 equinox and June 2015 solstice. The observed differences in SWA and SWB results could be explained by the longitude/LT separation between satellites, as SWB crossed the same post-sunset sector increasingly later than the SWA did.

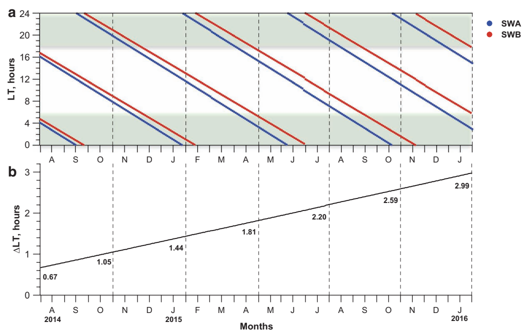

Figure 1

Keywords: Swarm; Plasma irregularities; Topside ionosphere; GPS; Langmuir probe; ROTI

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LETTER **Open Access**

A model of Earth's magnetic field derived from 2 years of Swarm satellite constellation data

Nils Olsen*, Christopher C. Finlay, Stavros Kotsiaros and Lars Tøffner-Clausen

Earth, Planets and Space 2016, **68**:124 DOI: 10.1186/s40623-016-0488-z
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Abstract

More than 2 years of magnetic field data taken by the three-satellite constellation mission *Swarm* are used to derive a model of Earth's magnetic field and its time variation. This model is called SIFMplus. In addition to the magnetic field observations provided by each of the three *Swarm* satellites, explicit advantage is taken of the constellation aspect of *Swarm* by including East–West magnetic intensity and vector field gradient information from the lower satellite pair. Along-track differences of the magnetic intensity as well as of the vector components provide further information concerning the North–South gradient. The SIFMplus model provides a description of the static lithospheric field that is very similar to models determined from CHAMP data, up to at least spherical harmonic degree n=75. Also the core field part of SIFMplus, with a quadratic time dependence for n≤6 and a linear time dependence for n=7–15, demonstrates the possibility to determine high-quality field models from only 2 years of *Swarm* data, thanks to the unique constellation aspect of *Swarm*. To account for the magnetic signature caused by ionospheric electric currents at polar latitudes we co-estimate, together with the model of the core, lithospheric and large-scale magnetospheric fields, a magnetic potential that depends on quasi-dipole latitude and magnetic local time.

Keywords: Geomagnetism; Field modeling; *Swarm* satellites

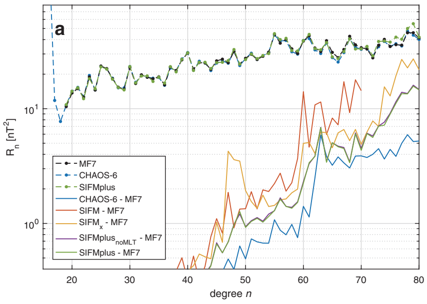

Figure 1

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LETTER **Open Access**

A Swarm lithospheric magnetic field model to SH degree 80

Erwan Thébault*, Pierre Vigneron, Benoit Langlais and Gauthier Hulot

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Abstract

The Swarm constellation of satellites was launched in November 2013 and since then has delivered high-quality scalar and vector magnetic field measurements. A consortium of several research institutions was selected by the European Space Agency to provide a number of scientific products to be made available to the scientific community on a regular basis. In this study, we present the dedicated lithospheric field inversion model. It uses carefully selected magnetic field scalar and vector measurements from the three Swarm satellites between March 2014 and December 2015 and directly benefits from the explicit expression of the magnetic field gradients by the lower pair of Swarm satellites. The modeling scheme is a two-step one and relies first on a regional modeling approach that is very sensitive to small spatial scales and weak signals which we seek to describe. The final model is built from adjacent regional solutions and consists in a global spherical harmonics model expressed between degrees 16 and 80. The quality of the derived model is assessed through a comparison with independent models based on Swarm and the CHAMP satellites. This comparison emphasizes the high level of accuracy of the current model after only 2 years of measurements but also highlights the possible improvements which will be possible once the lowest two satellites reach lower altitudes.

Keywords: Geomagnetism; Swarm; Lithosphere

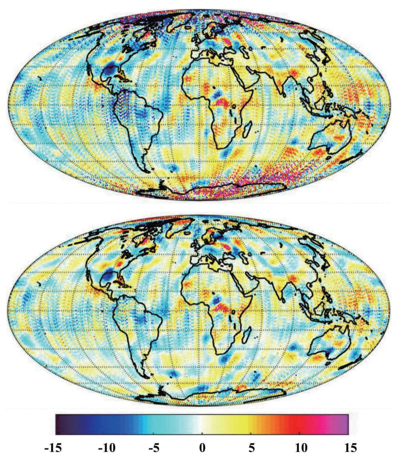

Figure 2

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LETTER **Open Access**

High-latitude ionospheric irregularities: differences between ground- and space-based GPS measurements during the 2015 St. Patrick's Day storm

Iurii Cherniak* and Irina Zakharenkova

Earth, Planets and Space 2016, **68**:136 DOI: 10.1186/s40623-016-0506-1
Received: 31 December 2015, Accepted: 6 July 2016, ublished: 30 July 2016

Abstract

We present an analysis of ionospheric irregularities at high latitudes during the 2015 St. Patrick's Day storm. Our study used measurements from ~2700 ground-based GPS stations and GPS receivers onboard five low earth orbit (LEO) satellites—Swarm A, B and C, GRACE and TerraSAR-X—that had close orbit altitudes of ~500 km, and the Swarm in situ plasma densities. An analysis of the rate of TEC index (ROTI) derived from LEO–GPS data, together with Swarm in situ plasma probe data, allowed us to examine the topside ionospheric irregularities and to compare them to the main ionospheric storm effects observed in ground-based GPS data. We observed strong ionospheric irregularities in the topside ionosphere during the storm's main phase that were associated with storm-enhanced density (SED) formation at mid-latitudes and further evolution of the SED plume to the polar tongue of ionization (TOI). Daily ROTI maps derived from ground-based and LEO–GPS measurements show the pattern of irregularities oriented in the local noon–midnight direction, which is a signature of SED/TOI development across the polar cap region. Analysis of the Swarm in situ plasma measurements revealed that, during the storm's main phase, all events with extremely enhanced plasma densities (>10^6 el/cm^3) in the polar cap were observed in the Southern Hemisphere. When Swarm satellites crossed these enhancements, degradation of GPS performance was observed, with a sudden decrease in the number of GPS satellites tracked. Our findings indicate that polar patches and TOI structures in the topside ionosphere were predominantly observed in the Southern Hemisphere, which had much higher plasma densities than the Northern Hemisphere, where SED/TOI structures have already been reported earlier. LEO–GPS data (ROTI and topside TEC) were consistent with these results.

Keywords: Topside ionosphere irregularities; Geomagnetic storm; GPS; ROTI; SED; TOI; Polar patch

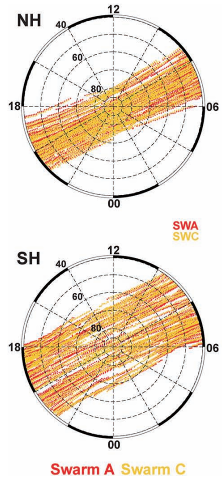

Figure 1

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LETTER **Open Access**

Localized field-aligned currents and 4-min TEC and ground magnetic oscillations during the 2015 eruption of Chile's Calbuco volcano

Tadashi Aoyama*, Toshihiko Iyemori, Kunihito Nakanishi, Michi Nishioka, Domingo Rosales, Oscar Veliz and Erick Vidal Safor

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Abstract

The Calbuco volcano in southern Chile erupted on April 22, 2015. About 2 h after the first eruption, a Swarm satellite passed above the volcano and observed enhancement of small-amplitude (~0.5 nT) magnetic fluctuations with wave-packet structure which extends 15° in latitude. Similar wave packet is seen at the geomagnetic conjugate point of the volcano. Just after the eruption, geomagnetic fluctuations with the spectral peaks around the vertical acoustic resonance periods, 215 and 260 s, were also observed at Huancayo Geomagnetic Observatory located on the magnetic equator. Besides these observations, around 4-min, i.e., 175, 205 and 260 s, oscillations of total electron content (TEC) were observed at global positioning system stations near the volcano. The horizontal propagation velocity and the spatial scale of the TEC oscillation are estimated to be 720 m/s and 1600 km, respectively. These observations strongly suggest that the atmospheric waves induced by explosive volcanic eruption generate TEC variation and electric currents. The Swarm observation may be explained as a manifestation of their magnetic effects observed in the topside ionosphere.

Keywords: Magnetic field; Magnetic fluctuation; Field-aligned current; Acoustic gravity wave; Middle latitudes; Atmospheric wave; Ionospheric dynamo; Volcanic eruption; Total electron content; Ionospheric disturbance

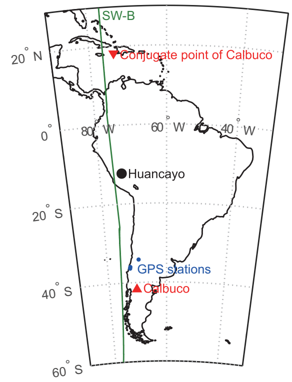

Figure 1

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LETTER Open Access

Prompt penetration electric fields and the extreme topside ionospheric response to the June 22–23, 2015 geomagnetic storm as seen by the Swarm constellation

Elvira Astafyeva*, Irina Zakharenkova and Patrick Alken

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Abstract

Using data from the three *Swarm* satellites, we study the ionospheric response to the intense geomagnetic storm of June 22–23, 2015. With the minimum SYM-H excursion of −207 nT, this storm is so far the second strongest geomagnetic storm in the current 24th solar cycle. A specific configuration of the Swarm satellites allowed investigation of the evolution of the storm-time ionospheric alterations on the day- and the nightside quasi-simultaneously. With the development of the main phase of the storm, a significant dayside increase of the vertical total electron content (VTEC) and electron density Ne was first observed at low latitudes on the dayside. From ~22 UT of 22 June to ~1 UT of 23 June, the dayside experienced a strong negative ionospheric storm, while on the nightside an extreme enhancement of the topside VTEC occurred at mid-latitudes of the northern hemisphere. Our analysis of the equatorial electrojet variations obtained from the magnetic Swarm data indicates that the storm-time penetration electric fields were, most likely, the main driver of the observed ionospheric effects at the initial phase of the storm and at the beginning of the main phase. The dayside ionosphere first responded to the occurrence of the strong eastward equatorial electric fields. Further, penetration of westward electric fields led to gradual but strong decrease of the plasma density on the dayside in the topside ionosphere. At this stage, the disturbance dynamo could have contributed as well. On the nightside, the observed extreme enhancement of the Ne and VTEC in the northern hemisphere (i.e., the summer hemisphere) in the topside ionosphere was most likely due to the combination of the prompt penetration electric fields, disturbance dynamo and the storm-time thermospheric circulation. From ~2.8 UT, the ionospheric measurements from the three Swarm satellites detected the beginning of the second positive storm on the dayside, which was not clearly associated with electrojet variations. We find that this second storm might be provoked by other drivers, such as an increase in the thermospheric composition.

Keywords: Swarm mission; Geomagnetic storm; Ionosphere; TEC; Electron density; Prompt penetration electric field; EEJ/EEF; Counter electrojet; Topside ionosphere

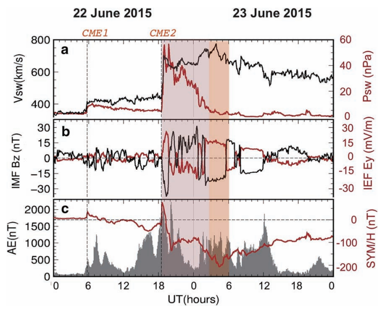

Figure 1

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