Swarm 10 Year Anniversary and Science Conference 2024

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ABSTRACT BOOK

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1. Swarm-based empirical models of high-latitude ionospheric electrodynamics

Dr. Spencer Hatch[1], Dr. Heikki Vanhamäki[2], Dr. Johnathan K Burchill[3], Dr. David J Knudsen[3], Dr. Karl Magnus Laundal[1], Dr. Levan Lomidze[3], Dr. Jone Peter Reistad[1]

1Universiteteti of Bergen, Bergen, Norway, 2University of Oulu, Oulu, Finland, 3University of Calgary, Calgary, Canada

Ionospheric electrodynamics is a problem of mechanical stress balance mediated by electromagnetic forces. Joule heating (the total rate of frictional heating of thermospheric gases and ionospheric plasma) and ionospheric Hall and Pedersen conductances comprise three of the most basic descriptors of this problem. More than half a century after identification of their central role in ionospheric electrodynamics, several important questions about these parameters — including the degree to which they actually exhibit hemispheric symmetry — remain unanswered. While global estimates of these parameters can be obtained by combining existing empirical models, one often encounters some frustrating sources of uncertainty: the measurements from which such models are derived, usually magnetic field and electric field or ion drift measurements, are typically measured separately and do not necessarily align. The models to be combined moreover often use different input parameters, different assumptions about hemispheric symmetry, and/or different coordinate systems. We eliminate these sources of uncertainty in model predictions of electromagnetic work (in general not equal to Joule heating) and ionospheric conductances by combining two new empirical models of the high-latitude ionospheric potential and ionospheric currents that are derived in a mutually consistent fashion: these models do not assume any form of symmetry between the two hemispheres; are based on Apex coordinates, spherical harmonics, and the same model input parameters; and are derived exclusively from convection and magnetic field measurements made by the Swarm and CHAMP satellites. We illustrate the utility of these new models by comparing high-latitude distributions of electromagnetic work and ionospheric Hall and Pedersen conductances in each hemisphere as functions of dipole tilt and interplanetary magnetic field clock angle. The distinction between electromagnetic work and Joule heating allows us to identify where and under what conditions our implicit assumption that the neutral wind corotates with the earth is not likely to be physically consistent with predicted Hall and Pedersen conductances.

2. A Swarm of jerks: Using the spatial gradient tensor for core-surface flow modelling.

Mr Frederik Dahl Madsen1, Prof. Kathy Whaler1, Dr. Ciarán Beggan2, Dr. Will Brown2, Prof. Richard Holme3

1.The University of Edinburgh, Edinburgh, United Kingdom, 2.British Geological Survey, Edinburgh, United Kingdom, 3.University of Liverpool, Liverpool, United Kingdom

The tri-satellite ESA Swarm mission allows along- and across-track differences of magnetic field measurements, making it possible to generate spatial gradients of the geomagnetic field and its secular variation (SV). Inverting the SV spatial gradient tensor for core-surface flows allows us to investigate the Earth's outer core with higher spatial resolution than using vector component data. We compare inversions from vector and tensor datasets, with a particular focus on the 'swarm' of geomagnetic jerks observed in the Pacific region during the Swarm mission period.
We invert for core-surface flow models directly from the SV data, without the use of stochastic or numerical models, imposing flow equatorial symmetry, quasi- or tangential geostrophy, or band-pass filtering. We develop two different flavours of model, both damped to minimise spatial complexity and minimise acceleration between epochs. The first set of models is otherwise unconstrained. In the second set, we relax the temporal damping on certain flow coefficients, to allow for features such as torsional oscillations to exist. We predict the intradecadal variation in length-of-day (ΔLOD) from each model, and find that only the model which allows for torsional oscillations follow the general trend of the observed ΔLOD.
We observe three jerks in the Pacific region from the Swarm data– in 2017, 2020, and at the end of 2022. The azimuthal component of flow acceleration of all models shows evidence of fast westward low-latitude waves. During the 2017 and 2020 Pacific region geomagnetic jerks, our models show a standing wave-like phenomenon in this region, time-centred between the two jerks. Previous research suggests that jerks may originate from Alfvén wave packets emitted from the inner-outer core boundary. We propose that the observed wave may occur when these wave-packets constructively interfere with existing Magneto-Coriolis waves at the core surface.
Finally, we examine the use of spatial gradients from the CHAMP mission, which allows us to compare the quality of core surface flow models from the CHAMP and Swarm missions. We find that the CHAMP data is of lower quality, and we are unable to observe this proposed wave-interaction, highlighting the unprecedented accuracy of the Swarm mission.

3. Magneto-Coriolis waves in Earth's core

Dr Nicolas Gillet1

[1]Isterre / CNRS, Grenoble, France

Over two decades of satellite magnetic observations have revealed the existence of wave-like patterns in the Earth's core at interannual periods. Thank to new theoretical developments and advances in numerical simulations of the geodynamo, they have been interpreted as the signature of Magneto-Coriolis waves. Reanalyses of longer records covering the observatory era suggest the existence of similar waves over a wide range of time-scales. This renewed understanding of the magnetic signal in a deterministic framework opens several avenues of research, among which: reconstructing the dynamo field in the bulk of the core, sounding the electrical conductivity of the deep mantle, or predicting the core field evolution.

4. Exploring a radial ionospheric current associated with the sunlight terminator

Kaitlin Dumoulin[1], Karl M. Laundal[1], Norah Kwagala[1]

[1]Department of Physics and Technology, University of Bergen, Bergen, Norway

Field-aligned currents (FACs) and its effects on the ionosphere are crucial for the understanding of the circulation of energy in space around Earth. The currents that are moving along the magnetic field lines are primarily driven by the solar wind and they couple to horizontal electric currents in the ionosphere. Two components of the horizontal currents are the Hall and Pedersen currents. Hall currents flow perpendicular to both the electric and magnetic fields, while Pedersen currents flow parallel to the electric field. According to the ionospheric Ohm's law there should be field-aligned currents at the sunlight terminator due to conductance gradients. The analysis uses the PC index to characterise the electric field and a model of the gradient of the Hall conductivity due to solar EUV radiation. Currently, we calculate the FACs based on vector magnetic field measurements from Swarm with the CHAOS model subtracted. We are looking at latitudes > 80 degrees to find currents that are not influenced by field-aligned current in the auroral zone and investigate data from orbits that are almost perpendicular to the terminator. The goal of this research is to find if there is a significant radial ionospheric current associated with gradients in the Hall conductance.

5. Nightside Magnetospheric models from a decade of SWARM measurements

Dr Natalia Gomez Perez[1], Dr Ciaran D Beggan[1]

[1]British Geological Survey, Edinburgh, United Kingdom

The magnetosphere varies with periodicities of tens of years, seasonal and daily variations. Using satellite observations from the SWARM constellation we determine the time-varying geometry of the magnetosphere using a degree and order 3 model. Thanks to the continuous and consistent measurements from SWARM we can analyse the variation in the geometry of the night-side magnetosphere. We now have 10 years of continuous measurements of the magnetospheric variation, which covers most of a solar cycle.
The Swarm-based models show evidence of the solar cycle variation, and the average night side ring current strength variability with long periods. We observe the seasonal Russell-McPherron effect in the 10 years averaged magnetosphere, and we also observe a dusk-dawn asymmetry on the nightside ring current.

6. Core flow ingredient: sensitivity to the geodynamo priors

Dr Hannah Rogers[1], Dr Nicolas Gillet[1], Dr Julien Aubert[3], Dr Mioara Mandea[2]

[1]Isterre, Grenoble, France, [2]CNES, Paris, France, [3]IPGP, Paris, France

A prior information extracted from geodynamo simulations is now routinely used for the reconstruction of fluid motions within the Earth's core from magnetic data. Here we investigate the sensitivity of the inverted flow models to the considered dynamo prior. We show that the quasi-static motions are sensitive to the nature of the simulated forcing (e.g. isotropic or not) and to the core-mantle couplings (gravitational and electro-magnetic) considered in the numerical set-up. Meanwhile, transient interannual to decadal inverted motions show less variability among the various investigated priors. We attribute this to long periods flow motions generating relatively little induction (in proportion of their magnitude) in comparison with rapid flow variations, because for slow enough changes the field and flow have time to align so as to minimize induction.

7. Field Aligned Current density intensification during a substorm: Swarm observations

PhD Dr Lorenzo Trenchi[1], Dr Nicola Plutino[2], Giuseppe Pallocchia[3]

[1]Serco For Esa, Frascati, Italy, [2]Department of Physics University of Rome Tor Vergata, Roma, Italy, [3]Istituto Nazionale di Astrofisica, Istituto di Astrofisica e Planetologia Spaziali, Roma, Italy

In this paper, we present a comprehensive analysis of Field-Aligned Current (FAC) measured by Swarm constellation during the moderate substorm on November 3 and 4 2021, when all three Swarm s/c were orbiting in 06–18 LT sectors, providing high sampling rate of both northern and southern auroral ovals.

Swarm FAC data are compared to the geomagnetic activity indices that monitor the intensity of the auroral electrojet and the ring current. In particular, we analysed two Super-MAG high-resolution indices, SYM-H and SME, which are both available at one-minute time resolution and allow to assess the ionospheric response on shorter time scales.

Swarm AEBS Level2 data products are utilized to identify the auroral oval and separate Region1 and Region2 FACs in Swarm data, and different smoothing procedures are applied to investigate FAC behaviour across varying spatial scales. Time delays between the Swarm FAC data and the geomagnetic indices are also introduced to unravel the delayed response of the different current systems.

Through linear correlation analysis, we found that FAC and SME reacts almost simultaneously, with an optimal time shift of 2 minutes between them, and a robust correlation coefficient of nearly 0.8 across all spatial scales examined. At the same time, the optimal time shift between FAC and SYM-H is almost 4 hours, displaying a correlation coefficient near 0.7.

These results suggest that high-resolution Swarm FAC data can provide complementary information to assess the intensity and time evolution of ionospheric current system, offering valuable insights into ionospheric dynamics during geomagnetic storms.

8. Plasma bubbles in the top side ionosphere: from automatic detection to possible sources

Dr Giulia D'angelo[1], Dr Emanuele Papini[1], Dr Alessio Pignalberi[2], PhD student Dario Recchiuti[3], Dr Piero Diego[1], Dr Mirko Piersanti[4]

[1]Inaf-iaps, Rome, Italy, [2]INGV, Rome, Italy, [3]Università degli Studi di Trento, Trento, Italy, [4]Università degli Studi dell'Aquila, L'Aquila, Italy

Equatorial Plasma Bubbles (EPBs) are plasma density depletions observed in the equatorial ionosphere at different spatial and temporal scales. Typically, they occur within a narrow band of ±20° latitude, at altitudes between the bottom side of the ionospheric F region and up to ~1000 km.
Generically, they appear at local dusk where the pre-reversal enhancement of the eastward electric field can elevate the F layer to higher altitudes, thereby increasing the Rayleigh–Taylor instability growth rate. However, EPBs are also observed during geomagnetic storms when the Prompt Penetration Electric Fields (PPEFs) of magnetospheric origin and/or the ionospheric disturbance dynamo can generate electric field perturbations, which can either suppress or favour the development of such irregularities.

Here, we present a statistical comparison between the main characteristics of the EPBs observed by Swarm B and CSES-01 satellites in the time frame from 2019 to 2021. EPBs have been automatically detected through a new technique based on both in-situ electron density (Ne) observations by Langmuir Probes (LPs) and CSES-01 electric field observations.

9. Using SOLA for investigating rapid fluctuations of outer core surface flow

Dr Hannah Rogers[1], François Dall'Asta[1], Dr Nicolas Gillet[1], Dr Chris Finlay[3], Dr Magnus Hammer[3], Dr Mioara Mandea[2]

[1]Isterre, Grenoble, France, [2]CNES, Paris, France, [3]DTU Space, Copenhagen, Denmark

The SOLA (Subtractive Optimally Localised Averages) methodology allows us to create point estimates of radial field time evolution at any desired location at the core surface by considering a weighting of global satellite measurements in a spatio-temporal trade-off. Producing localised-average estimates at the top of the core bypasses problems with downward continuing data. SOLA data outputs (including the localising kernel) are incorporated into the PyGeodyn data assimilation tool for producing core surface flow models. We use this approach to track additional information on wave-like flow motions at the top of the Earth's core, in particular in the equatorial region where these motions are thought to be most prominent. We show how using SOLA data within the PyGeodyn algorithm can help investigate rapid fluctuations in core surface flows and provide finer temporal and spatial resolution than with Gauss coefficient magnetic data.

10. Reconstruction of 3-D Core Flow from Geomagnetic Satellite Data

Dr Yufeng Lin[1], Jinfeng Li[1], Keke Zhang[2]

[1]Southern University of Science and Technology, Shenzhen, China, [2]Macau Institute of Space Technology and Application, Macau, China

The Earth's magnetic field is generated in the liquid outer core through the dynamo action. Although the dynamo theory has been proposed and studied for a century, we still do not understand well how the geodynamo is operating in the liquid outer core. Continuous satellite measurements of the Earth's magnetic field have been available since 1999, which can provide important constraints on the core dynamics. In this talk, we present a novel method for reconstructing 3-D core flows from geomagnetic satellite data. The method relies on an expansion of inertial modes, which are eigen modes of a rotating fluid system and thus can be used to describe the rotation-dominated core flow. The inverse problem becomes retrieving the coefficients of inertial modes, which is solved based on Physics-Informed Neural Networks (PINNs). PINNs provide a function approximation of the core flow which satisfies the physical constraints and matches the observed geomagnetic field variations. We first perform a twin experiment using synthetic observations from Earth-like geodynamo simulations and demonstrate that the method can retrieve large-scale 3-D core flow from geomagnetic observations. We then use geomagnetic observations from Swarm and MSS-1 Satellites to reconstruct 3-D core flows. The preliminary results reveal the distinct east-west hemispheric asymmetry of the core flow.

11. Operating a satellite constellation: how we keep Swarm flying

Mr. Giuseppe Albini[1], Mr. David Patterson, Mr. Alessandro Latino, Mr. Emanuele Lovera, Mr. Angel Fernandez Lois, Mr. Thomas Demeillers, Mr. Filippo Inno, Mrs. Anne Hartmann, Mr. Giuseppe Romanelli

[1]ESA, Darmstadt, Germany

The Swarm Flight Operations Segment (FOS) at the European Space Operations Centre (ESOC) in Darmstadt, Germany takes care of Swarm in-orbit operations since the first acquisition of signal after the separation from the launcher on 22/11/2013. Since then, the effort of the FOS teams have allowed to go through the Early Orbit Phase, the platform and instruments commissioning and many years of routine operations.

The presentation will go through the description of the Flight Operations Segment, its elements and structures, the approach to operations and how routine and contingencies are carried out and responded to.

The layout of the Swarm FOS, similarly to the one of any other Earth Observation mission at ESOC, is composed by elements of the ground segment that will be presented as pieces of a puzzle, each one contributing to key elements necessary to keep the constellation flying: the ESA's and partners network of ground stations, the Mission Control System, the Mission Planning System, the Flight Dynamics, the operational infrastructure and data dissemination systems and Space Debris system, to name a few.

The way these systems work, and the effort spent year after year to counteract their obsolescence and increase the level of automation within the ground segment, is described.

Also, all interfaces between the FOS and the remaining ground segment entities will be also named and presented. This presentation will therefore offer an updated view of the Swarm ground segment, with particular emphasis on the Flight Operations Segment and the operational approach, together with a snapshot offering the status of on-board and ground segments.

12. A geomagnetic field model incorporating Earth's mantle conductivity

Dr. Hongbo Yao[1], Prof. Dr. Keke Zhang[1]

[1]Macau Institute of Space Technology and Application, Macao, China

The magnetic fields measured by ground observatories and satellites include various contributions from the core, crust, ocean, ionosphere, and magnetosphere, as well as their Earth induced counterparts. Separating the magnetic fields of different contributions through geomagnetic field modeling is a highly challenging task. In previous geomagnetic field models, the induced magnetic fields due to magnetospheric current systems are commonly considered by separating the Dst or RC index into external and internal parts using an a priori 1-D Earth conductivity model. However, to derive the 1-D conductivity model, it is necessary to isolate the time-varying magnetospheric magnetic field from magnetic measurements by subtracting the core and crustal fields as predicted by a given geomagnetic model (which was derived by assuming an a priori 1-D conductivity model). This introduces errors in both geomagnetic field modeling and Earth's mantle conductivity imaging. To improve the accuracy of geomagnetic field models and to better image mantle conductivity structure, we consider mantle conductivities as model parameters in the process of geomagnetic field modeling. Using the geomagnetic field model of the magnetosphere as an example, we implement this method in an alternating manner that encompasses the following steps: (1) we estimate external source coefficients using an a priori mantle conductivity model; (2) we invert the profile of mantle conductivity using the recovered source coefficients; and (3) we repeat steps (1)-(2) to iteratively update source coefficients and the profile of mantle conductivity until convergence. Numerical experiments demonstrate that our approach can accurately reconstruct the prescribed time series of external source coefficients and mantle conductivity structure after a few iterations. This approach will be used to derive a new comprehensive geomagnetic field model using MSS-1 satellite magnetic observations, complemented by data from additional satellite missions such as Swarm.

13. Ion mass estimations by the Swarm electric field instrument (EFI)

Dr. Matthias Foerster[1], Dr. Johnathan Burchill, Dr. Lewan Lomidze

[1]GFZ Potsdam, Potsdam, Germany

The present default Langmuir Probe (LP) algorithm for estimating the plasma density relies on three major suppositions: the orbital motion limited (OML) theory is applicable, the surrounding plasma consists of pure oxygen ions only, and the along-track ion velocity coincides with the spacecraft orbital speed. These assumptions are routinely violated, particularly with respect to ion composition on the nightside and during periods of low solar activity as well as at auroral and polar latitudes, where ion drifts of magnetospheric origin are dominating. Both factors are compromising the accuracy of the plasma density measurements. Further, numerical simulations of the spacecraft's plasma environment and observational results have shown that plasma shielding effects are not negligible. These effects have been taken into account with the novel SLIDEM (Swarm LP Ion Drift and Effective Mass) product, which also yields improved estimates of the plasma density, the along-track ion drift and the effective ion mass along the orbital path. This is done by additional use of the ion current to the faceplate at Swarm's front side. It will be shown, that the measurements of the Langmuir probe alone can result in reliable ion mass and accordingly revised plasma density estimations.

14. Swarm-E GPS Observations of the Polar Cap Ionosphere

Dr Chris Watson[1], Dr Richard Langley[1], Dr. Andrew Howarth[2], Dr. Andrew Yau[2]

[1]University Of New Brunswick, Fredericton, Canada, [2]University of Calgary, Calgary, Canada

The Global Positioning System (GPS) Attitude, Positioning, and Profiling (GAP) instrument is one of eight components of the scientific instrument suite onboard the Swarm-E satellite (previously CASSIOPE/e-POP). The Swarm-E instrument suite was designed to primarily study the physical processes coupling the polar ionosphere to the solar wind and magnetosphere, and the ionospheric structure and dynamics associated with this coupling. The GAP instrument consists of three GPS antennas oriented towards spacecraft zenith and one antenna oriented in the anti-ram direction, along with associated GPS receivers. This configuration allows for both radio occultation and topside ionosphere measurements, which are collected at data rates of up to 100 Hz. The elliptical, polar orbit of Swarm-E and high data rate of GAP allows for unique radio occultation and topside ionosphere observations, which is particularly useful for polar regions where much of the ionosphere structure and dynamic behaviour associated with SW-M-I-T coupling are not well observed or understood.

The presentation will discuss recent reprocessing of GAP data and ongoing research projects employing the GAP dataset. More than ten years of GAP data (starting in September 2013) have been reprocessed, with calibrated line-of-site total electron content (TEC), Vertical TEC, and electron density profile data products currently available on the epop-data website (https://epop.phys.ucalgary.ca/data/). We will discuss the climatology of polar cap VTEC, in addition to concurrent observations of the Imaging and Rapid-scanning ion Mass spectrometer (IRM) of Swarm-E, which provides simultaneous observations of topside polar ionosphere electron content and ion outflow, an important coupling mechanism within the solar wind-magnetosphere-ionosphere system. We will also demonstrate the utility of GAP electron density profiles, which provide electron density values up to 1500 km altitude in the polar cap.

15. MSS-1 data processing and initial model based on Swarm data

Mr YI Jiang[1]

[1]Macao University Of Science And Technology, Macao, China

We describe the results of vector magnetic data calibration by comparison with scalar magnetometer. Five month data were selected and the agreement between the two magnetometers after calibration less than 0.3 nT RMS.
We also report the determination of Euler angles by modeling together with MSS-1 and Swarm magnetic field data. The MSS-1 initial field model (MIFM) include 30 degree internal field and 2 degree external field. The model shows the very good consistent between MSS-1 data and Swarm data. The RMS of MSS-1 scalar and vector data are 1.81nT and 3 nT, respectively.

16. Study the local time asymmetry of the Earth's ring currents by magnetic surveys of multiple low-Earth-Orbit satellites.

Dr. Jiaming Ou[1], Dr. Yi Jiang, Mr. Qing Yan[1]

[1]Macau University Of Science And Technology, Macau, China

The azimuthal morphology of the Earth's ring currents was reported always asymmetric during extreme space weather events at low latitudes, such as geomagnetic storms. A dawn-dusk pattern was detected during the storm main phase with near-Earth and in-situ magnetic measurements. This property is proposed to be generated from the asymmetric solar wind – magnetosphere coupling, being related to the ring current closures. Recently evidence was confirmed that asymmetric ring currents exist in quiet times and storm recovery phase. Such phenomenon may bear close relation to the evolutions of ring currents, including plasma injection and decay processes. In this study, the local time asymmetry of the ring current is estimated by low-Earth-Orbit Swarm and Macau Science Satellite-1 (MSS-1) missions. Spherical harmonics models are developed to quantify the energy of ring currents by external Gauss coefficients during quiet periods and storm recovery phase, respectively.

17. A cubed-sphere based regional model for lithospheric magnetic field

Doctor Liang Yin[1], Pengfei Liu[1], Jinsong Du[2]

[1]Macau Institute of Space Technology and Application, Macao, China, [2]China University of Geosciences, Wuhan, China

The lithospheric contribution to the Earth's magnetic field data, which have been measured from ground to satellite altitudes over several decades, is difficult to be precisely identified. One way to alleviate this difficulty is combining multi-level magnetic field observations at different altitudes, such as satellite data of globally high spatial coverage, and aeromagnetic data of regionally high spatial resolution. To achieve the goal, a model with capability of handling both regional and global data is required. In this report, we propose a new regional model for lithospheric magnetic field based on non-uniform cubed-sphere grid, which supports flexible local refinement and can be applied to global, regional, and combined model for lithospheric field. Several numerical tests are performed to validate the accuracy and efficiency.

18. Satellite Laser Ranging to Swarm satellites: validation, modeling of systematic effects, determination of global geodetic parameters, and realization of terrestrial reference frame

Dr Dariusz Strugarek[1], Prof. Krzysztof Sośnica[1]

[1]Wrocław University of Environmental and Life Sciences, Wrocław, Poland

Swarm-ABC satellites require precise orbit determination (POD) products to reach their mission goals, such as exploration of Earth's geomagnetic field and electric field in the upper atmosphere, and others. Swarm spacecraft are equipped with Global Positioning System (GPS) receivers to provide the POD products and with laser retroreflectors, which allow for satellite tracking using the Satellite Laser Ranging (SLR) technique. SLR allows for an independent validation of the orbits calculated using GPS. SLR measurements are provided by a global network of stations coordinated by the International Laser Ranging Service (ILRS). Many of them consider Swarm targets as the ILRS supports their tracking since the beginning of the mission.

We show the ILRS contribution to the Swarm mission for the whole period of the mission (up to 2023.5). We perform SLR-based validation of the POD products of Swarm satellites provided by the ESA and show their quality assessment. We demonstrate that laser measurements to Swarm satellites can be successfully used not only for orbit validation, but also for determination of geodetic parameters, SLR station coordinates or modeling systematic effects affecting SLR measurements, such as range, tropospheric, or distance-dependent biases. When estimating range biases, the consistency between Swarm SLR residuals to GPS POD products is improved from 10 to 8 mm whereas the tropospheric biases further improve the consistency to the level of 6 mm. Moreover, we investigate the possible deficiencies in the performance of SLR stations grouped by used detector type and the possibility for calculation of global geodetic parameters provided by Swarm orbits, such as geocenter, length-of-day excess, and pole coordinates. Finally, we show that high-quality POD products and SLR measurements to Swarm satellites allow for the determination of SLR station coordinates by using the network constraining approach or the so-called 'SLR-PPP' approach which are characterized with repeatability of coordinate components at the level of less than 20 mm and high consistency with SLRF14/20 solutions.

19. Comprehensive Magnetic Field Inversion from 10 Years of Swarm Data

Mr Lars Tøffner-Clausen[1]

[1]DTU, Kgs Lyngby, Denmark

We present the results of the Comprehensive Inversion (CI) magnetic field model processing chain conducted by the Swarm DISC team at DTU Space and NASA Goddard using 10 years of Swarm data complemented by data from geomagnetic ground observatories around the world as well as calibrated platform magnetometer data from the CryoSat-2 mission. The CI chain takes full advantage of the Swarm constellation by doing a comprehensive co-estimation of the magnetic fields from Earth's core, lithosphere, ionosphere, and magnetosphere together with induced fields from Earth's mantle and oceans using single and dual satellite gradient information.

20. A study on the local time variation of the occurrence of equatorial plasma bubbles during various geomagnetic storms for the period from 2015 to 2022

Remya S Nair[1], Megha M Nair, **Arathi S**

[1]Department of Physics, NSS Hindu College, Changanacherry, Kerala 686 102, India

This study investigates the local time variation of equatorial plasma bubble (EPB) occurrence during geomagnetic storms over an eight-year period, spanning from 2015 to 2022. Equatorial plasma bubbles, characterized by irregularities in ionospheric electron density, have significant implications for radio wave propagation and global positioning systems. Geomagnetic storms, driven by solar and interplanetary disturbances, can disrupt the equatorial ionosphere and influence EPB formation. Using data from SWARM, this research analyzes the temporal distribution of EPBs at the equatorial region and their correlation with geomagnetic storm activity. The study reveals distinct patterns in the occurrence of EPBs during different phases of geomagnetic storms, including the storm's initiation, main phase, and recovery period. The findings indicate that the occurrence of EPBs exhibits notable local time variations during geomagnetic storms. During the storm's main phase, a significant increase in EPB occurrence is observed particularly between 06:00 and 12:00 LT (local time). This enhanced EPB activity is attributed to the enhanced electric fields and plasma irregularities induced by the storm's dynamic processes.

21. Multi-scale magnetospheric and ground currents from Swarm, Cluster and MMS

Prof Malcolm Dunlop[1], Mr Xin Tan[2], Mr Chunming Zhang[2], Dr Junying Yang[2], Dr Xiangcheng Dong[3], Dr Dong Wei[4], Prof Chao Xiong[5]

[1]RAL Space, STFC , Didcot, United Kingdom, [2]SSE, BUAA, Beijing, China, [3]Yunnan University, Kunming, China, [4]Southern University of Science and Technology, Shenzhen, China, [5]Wuhan University, Wuhan, China

We cover a range of studies using distributed, multi-scale measurements arising from the coordination of the magnetic field at Swarm with Cluster, MMS and ground-based arrays. The scaling, coherence and correlation of field-aligned current sheets (FACs) connecting different regions of the magnetosphere at both low (LEO) and high altitudes have been explored with associated analysis techniques and in relation to the (R1/R2) auroral boundaries. Individual events can map conjugate current density distributions at the magnetopause, ring current and regions in between; as well as any associated ground signatures, as driven by the external conditions. The distribution FAC orientations in local time (MLT) and latitude (MLAT) can be inferred from dual-spacecraft (e.g. the Swarm A&C spacecraft) correlations, where the behaviour relates to the geomagnetic conditions and current closure (e.g. via electrojet currents). Conjugate effects between ground (dH/dt), ionospheric and magnetospheric magnetic signals show that intense, coherent FA currents can take place in the polar cusp during the main phase of a geomagnetic storm and at near tail local times during substorm activity, at different altitudes. Mesoscale cusp FACs show vertical scaling, driven by unsteady magnetic reconnection at the magnetopause. While intense dH/dt signals are shown to be associated with FACs driven into the ionosphere by the arrival of bursty bulk flows BBFs at geosynchronous orbit (linked via a modified sub-storm current wedge, SCW). In situ ring current morphology and the adjacent parallel currents can be compared to distributions of R2-FACs at Swarm.

22. LAI Coupling observation and research-from CSES, CSES/Swarm cooperation to IMCP

Xuhui Shen[1]

[1]National Space Science Center, CAS, Beijing, China

Being the first geophysical fields observation satellite mission of China, CSES-01 has operated for 5 years as scheduled by Feb.02, 2023 and on the basis of its fine performance, CSES-01 will prolong its life until CSES-02 lunching in orbit and collaborative work each other in orbit.
The last 6 years, in retrospect, CSES-01 acquired an amount of data such as geomagnetism field, low frequency electromagnetic waves, in-situ plasma content and temperature, charged particles as well ionospheric plasma CT, in which, more than 70 earthquakes with magnitude greater than 7 and 700 greater than 6 are recorded in globe, together with a series of space weather and volcano phenomenon were recorded. So far, we result positive knowledge on earthquake precursors according to the statistical research and case study of most of these events, and develop the Lithosphere-Atmosphere-Ionosphere Coupling mechanism focusing on its electromagnetic wave channel.
The following prospect plan, CSES-02 is under developing by China-Italy joint team and is due to launch in 2024, which means that we'll have 2 CSES satellites in orbit from 2024. Now we're demonstrating the new mission of IMCP-International Meridian Circle Project, which should be a ground-based observation network with its main objectives on monitoring the geomagnetical field, space weather and interaction among Lithosphere-Atmosphere-Ionosphere. And the main tasks of IMCP are global data sharing, joint research on space weather and natural hazards as well global change, and so on.

23. The current status of the CSES mission and the main scientific progress

Prof Zeren Zhima[1], Dr. Yanyan Yang

[1]National Institute Of Natural Hazards, Ministry Of Emergency Management Of China, Beijing

The China Seismo-Electromagnetism Satellite (CSES) is the space-based observation platform of China's stereoscopic earthquake observation system. Its scientific objective is to obtain the global geomagnetic field, the electromagnetic field (waves), the ionospheric plasma parameters, and high-energy particles for the monitoring the dynamic variation of the ionosphere and the seismo-ionospheric disturbances over China and its surrounding areas to make up for the deficiency of the ground-based observation system, exploring new ways of earthquake monitoring and prediction by using space science. The first test probe of the CSES series was successfully launched in February 2018, and now it has been stably operating in orbit for more than six years; The second one is an operational probe that will be launched in December, 2024. The in-flight commissioning test and cross-calibration work show that the CSES can provide good data quality to support geophysics and space physics studies. Many valuable scientific results have been obtained in recent years. The global geomagnetic reference model built by CSES data is the first global geomagnetic field model built by the pure Chinese satellite data, and the Chinese scientists are the first time to take an important role in the computation of the global geomagnetic reference model (IGRF) since more than a century. The ionospheric electron density 3D model based on CSES satellite data can well present the ionospheric structure characteristics. In the natural hazards monitoring, the CSES has shown good response-ability to the disturbances related to earthquakes, volcano eruptions, and geomagnetic storms. In terms of the Lithosphere-Atmosphere-Ionosphere coupling mechanism study, the full-wave calculation method can provide the electromagnetic field changes between the lithosphere-ionosphere waveguide and the wave propagation feature in the ionosphere. The results from the full-wave model prove the capability of the CSES satellite's electromagnetic payloads to detect low-frequency electromagnetic emissions induced from the earthquake epicenter. The simulation and observation studies suggest that th eCSES satellite can reflect the seismic activities, VLF transmitter, magnetic anomalies in the lithosphere, lightning activities in the atmosphere, etc. These recent scientific results show that the CSES is consistent with other similar types of electromagnetic satellites worldwide, indicating its great potential in scientific application.

24. Inter-annual Magneto-Coriolis waves in the Earth's core

Dr. Felix Gerick[1,2], Phil Livermore[3]

[1]Centre National D'Études Spatiales (CNES), Toulouse, France, [2]Royal Observatory of Belgium, Brussels, Belgium, [3]School of Earth and Environment, University of Leeds, Leeds, United Kingdom

Satellite geomagnetic field observations in recent decades reveal inter-annual secular variations on a global spatial scale, with a large part of these variations occurring near the equatorial region. Quasi-geostrophic (columnar) Magneto-Coriolis waves are one possible wave mechanism to explain parts of these variations (Gerick et al. 2021, Gillet et al. 2022). We are modeling and studying these waves to obtain better constraints on the steady magnetic field within the core.

25. The state of thermosphere, using ionosonde and Swarm C observations, during the storm of February 3, 2023 resulted in the loss of 38 SpaceX Starlink satellites.

Dr. Loredana Perrone, Prof Andrey Mikhailov

[1]Istituto Nazionale Di Geofisica E Vulcanologia, Roma, Italy

On 3 February 2022, SpaceX Starlink launching 49 satellites 38 have been lost due to enhanced neutral density associated with two moderate geomagnetic storms. The ionospheric storm was analyzed using mid-latitude ionosonde observatories: two in Europe, two in America and one in Australia. The thermospheric parameters were retrieved from the ionospheric observations and the neutral density from Swarm C accelerometer with the THERION method to understand which thermospheric parameters gave the main contribution to neutral gas density variations. A comparison of retrieved neutral gas density with empirical models MSISE00 and JB2008 is presented.

26. Thermosphere-Ionosphere Observing System Simulation Experiments

Timothy Kodikara[1], Eelco Doornbos[2], Tzu-Wei Fang[3], Liangliang Yuan[1]

[1]German Aerospace Center (DLR), Neustrelitz, Germany, [2]Royal Netherlands Meteorological Institute (KNMI), De Bilt, Netherlands, [3]National Oceanic and Atmospheric Administration (NOAA), Boulder, CO, USA

Multi-instrument in-situ sampling from satellite constellations provides critical data to better understand and manage the impact of space weather on the thermosphere-ionosphere system. In the Swarm DISC (data, innovation, and science cluster) project SWITCH (Space Weather in the Ionosphere-Thermosphere Cal/val Hub), we conduct observing system simulation experiments (OSSEs) to evaluate a thermosphere-ionosphere data assimilation framework. Here we present experiments using synthetic electron and neutral measurements from Swarm and future geospace dynamics constellation (GDC) missions. In this presentation, we demonstrate the capabilities of the assimilation framework and quantify the improvement that the assimilation of multi-point Swarm and GDC-like in-situ observations brings to the thermosphere-ionosphere modelling.

27. From a Swarm of satellites to a flock of birds

Dr Ciaran Beggan[1], Dr Urška Demšar, Dr Fernando Benitez Paez, Dr Jed Long

[1]British Geological Survey, Edinburgh, United Kingdom

In the past few decades, wildlife tags which can incorporate batteries, solar cells, timing, light sensors, GPS, accelerometers and basic magnetic sensors have been developed which are small enough to be attached to migratory animals. The location data from these tags can be deposited into publicly accessible databases such as MoveBank (www.movebank.org). These databases contain millions of times and locations of animals including whales and bats and many different species of birds. Such data offer an opportunity to analyse where and how the animals moved between locations particularly over long distances during their annual migration. However, there has been a barrier to understanding the magnetic field influence on the animal during its journey, which has been the inability to access the relevant magnetic data and to link these data to animal tracking data.

To overcome this block for non-magnetic experts, a software tool which integrates with viresclient was developed to allow animal movement researchers to use the time and location from wildlife tags to work out what the magnetic field was along the migration route. Within the code, the magnetic field is computed using data from the Swarm magnetic tri-satellite mission operated by the European Space Agency (ESA). We describe the use of this tool for modelling the magnetic field experienced by migrating birds, particularly during magnetic storms and demonstrate the use of Swarm data in research areas not originally envisaged for the mission.

28. Assessment of GPS-based accelerometry performance with adaptive filter settings

Dr Jose van den IJssel[1], Dr Christian Siemes[1], Prof Dr Pieter Visser[1]

[1]Delft University of Technology, Delft, Netherlands

High-quality GPS observations from low Earth orbiting (LEO) satellites can be used to derive thermosphere densities along the satellite orbit. Such GPS-derived densities are currently computed operationally for all three Swarm satellites, in the framework of the Swarm Data, Innovation, and Science Cluster. Considering the increasing number of LEO satellites equipped with GPS receivers, this so-called GPS-based accelerometry approach offers great potential for improving thermosphere models and for studying the influence of solar and geomagnetic activity on the thermosphere.

To better quantify the accuracy that can be obtained with this approach, we assess the performance using the GRACE mission as a test case. For this mission high quality accelerometer data are available, which we can use to validate our GPS-based results. In addition, the GRACE mission has experienced a large variation in density signals, which allows us to assess the performance under a large range of conditions.

We present our GPS-based accelerometry processing strategy, which is based on a Kalman filter approach. The radiation pressure accelerations are accurately modelled and empirical accelerations capture the remaining aerodynamic signal. The empirical accelerations are modeled as Gauss-Markov processes defined by a steady-state variance, process noise and correlation time, which require careful tuning. This applies in particular to the setting of the process noise in the along-track direction, due to the large variations in the encountered aerodynamic signal. Best performance is obtained when the process noise setting is adapted to these variations. Using these adaptive filter settings, results are shown for periods with low, moderate, and high density. In a next step, we will implement the improved filter settings into our regular Swarm GPS-derived density processing chain.

29. Monitoring Ionospheric Gradients using Swarm onboard GPS and Langmuir-probe data

M Mainul Hoque[1], Dr. Andres Cahuasqui[1], Dr. Norbert Jakowski[1], Dr. Stephan Buchert[2], Dr. Dmytro Vasylyev[1], Mr Martin Kriegel[1], Mr Paul David[1], Mr Youssef Tagargouste[1], Dr. Jens Berdermann[1], Dr. Klaus Nielsen[3]

[1]German Aerospace Center (DLR), Neustrelitz, Germany, [2]Swedish Institute of Space Physics (IRF), Uppsala, Sweden, [3]Technical University of Denmark - DTU Space , Lyngby, Denmark

Within the scope of MIGRAS project we developed two new data products focus on monitoring small to mid-scale plasma density irregularities with horizontal spatial scales in the order of about 100 km utilizing measurements from the coordinated flight of Swarm satellites A and C at an orbit height of about 460 km. Two new Swarm products are the total electron content (TEC) Gradient Ionosphere indeX (TEGIX) and the electron density (NE) Gradient Ionosphere indeX (NEGIX) derived from topside TEC and in-situ electron density measurements onboard GPS receivers and Langmuir probes. The TEGIX and NEGIX results during the St. Patrick‘s Day Storm on 17th March 2015 will be shown and discussed for both North-South and West-East components. For the same storm day, the NEGIX and TEGIX products are validated against the Gradient Ionosphere IndeX (GIX) derived from numerous ground GNSS stations data over the European region. We found that the North-South component of TEGIX and NEGIX products correlate very well with the same component of the ground-based GIX data. A prototype data product of NEGIX and TEGIX has been produced for the time period 2018-01-01 until 2018-06-30. The data set has nearly 2 million records of estimated density gradient TEGIX and NEGIX vectors. Considering six months of data, NEGIX is validated using basic statistical tests. Clear terminator related gradients at sunrise and sunset, i.e. ~6 and ~18 LT are observed. NEGIX product shows consistent results with gradients at equatorial crests ~+/- 20 deg. Also shows the signature of mid-latitude ionospheric trough (MIT) at ~+/- 60 deg latitude. A use case of NEGIX for ionospheric scintillation modelling is discussed. An innovative scintillation modelling technique shows that the high gradients of electron density visible in the NEGIX can cause high phase scintillations.

Acknowledgement:
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30. Asymmetric Huber distribution for geomagnetic data

Dr Callum Watson[1], Will Brown[1], Natalia Gomez Perez[1], Ciarán Beggan[1]

[1]British Geological Survey, Edinburgh, United Kingdom

It has long been noted that residual noise in geomagnetic measurements is skewed, particularly at high geomagnetic latitudes, and exhibits tails heavier than those from a Gaussian distribution. The usual method of accounting for this noise is to fit data to a Huber distribution - Gaussian near the mean, with exponential decay beyond a fixed cutoff. However, this distribution is symmetric, and thus the estimated value is offset in the direction of the noise.

In order to better model the noise that would be observed under quiet conditions, we consider an asymmetric Huber distribution, with maximum-likelihood estimates for the Huber cutoffs considered separately in each direction. In such a distribution the modal point on the probability distribution is not the mean, but is corrected for the bias seen in the noise. In our analysis, all statistical parameters are also allowed to differ by location. This is more computationally expensive than fixed cutoffs, but it retains the advantages of the Huber distribution's simplicity while giving a more accurate estimate of the quiet field at high latitudes. Such estimates could be used to improve Swarm data products such as Geomagnetic Virtual Observatories.

31. Developing a Regional Swarm FAST Data Hazard Variation Index

Dr Lauren Orr[1], Dr Ciaran Beggan[1], Dr William Brown[1]

[1]British Geological Survey, Edinburgh, United Kingdom

We investigate the use of the Swarm satellite near-real-time Fast Track (FAST) data for the determination of an along-track hazard indicator based on pre-computed threshold exceedances. To determine the location-dependent threshold above which we consider the magnetic field to be highly active, we compute the 20-second standard-deviation of the measurements along-track and create baseline thresholds from 10 years of Swarm data. Using the standard 1Hz Level1b LR MAG product downloaded from VirES, the core, crust and magnetospheric effects are first removed and the residuals are analyzed to determine quiet-time and geomagnetically active thresholds. The along-track residuals are binned into quasi-uniform grid cells to compute the typical variance expected in the region. From the variances we can determine threshold values for exceedance e.g. at the 99th percentile in each bin. If the value of the standard deviation computed from Swarm FAST data in any magnetic component exceeds the pre-determined thresholds within the bin, there is highly variable magnetic field in that region. This indicates that a localized increase in space weather hazard risk is likely to have occurred. We present our Swarm-specific index which can be directly compared to other indices such as Ap or Kp. Where calculated our index compares well to Kp and Hp60 and captures activity levels during both geomagnetic storms and quiet times. Using FAST Level1b data we can quantify the hazard on a per-orbit basis as soon as Swarm data are available, thus providing as close to near-real time geomagnetic activity monitoring as presently feasible. The methodology could also be applied to future missions with new configurations.

32. MagQuest Challenge Update

Mr Mike Paniccia[1]

[1]DoD, Saint Louis, United States

The MagQuest Challenge is an open prize competition that will potentially launch three cubesats into orbit to measure Earth's Magnetic field. In September 2023, MagQuest completed Phase 4a of the challenge with all three potential solvers Magnetometers passing NASA guidelines. The teams are currently building the cubesats with plans to launch TBD 2025.

This talk would provide a full update and future plans. I suspect it would best fit in the "Swarm and Beyond" session on Wednesday.

33. Simple Geomagnetic Field Model Forecast Assessments: Auto-regressive Methods and Machine Learning

Dr. Martin Rother[1], Dr. Monika Korte[1]

[1]GFZ German Research Centre for Geosciences, Potsdam, Germany

Some data products from Swarm satellite magnetic field measurements, in particular for creating 'fast' now-casting products based on near real-time satellite data, require the best possible geomagnetic core field model forecasts. Forecasting the non-linear core field evolution or secular variation (SV) is a challenging task.

Here, we compare not only basic, merely numeric (auto-regressive) approaches but also standard machine learning (ML) applications to tackle this task. With these tools we estimate forecasts in the range of one to five years for some of the available spline-based field models of the modern geomagnetic field. These estimates are assessed and summarized. For the upcoming IGRF some extrapolation tests can be useful to get an idea and some experience about the uncertainty of those numerical only predictions, in particular on ML approaches. This may outline an acceptable strategy for (still) non-physics based, classical IGRF-14 SV parent models.

34. Modelling the variability of the topside ionosphere: Coupling with the neutral atmosphere

Dr Alan Wood[1], Yaqi Jin[2], Lucilla Alfonsi[3], Luca Spogli[3], Eelco Doornbos[4], Gareth Dorrian[1], Jaroslav Urbar[5], Kasper van Dam[4], Daria Kotova[2], Rayan Imam[3], Mainul Hoque[6], Wojciech Miloch[2]

[1]University of Birmingham, Birmingham, United Kingdom, [2]University of Oslo, Oslo, Norway, [3]Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy, [4]The Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands, [5]Institute of Atmospheric Physics CAS, Prague, Czech Republic, [6]German Aerospace Center (DLR), Köln, Germany

The ionosphere is a highly complex plasma containing electron density structures with a wide range of spatial scale sizes. It is coupled to the neutral atmosphere in which it is embedded. Swarm is the European Space Agency's (ESA) first constellation mission for Earth Observation (EO), comprising multiple satellites in Low Earth Orbit (LEO). Numerous data products are available and those of particular relevance to the present study are the ionospheric data product IPDxIRR_2F and the thermospheric data product DNSxACC. The IPDxIRR_2F data product includes a measure of the ionospheric variability at a spatial scale of 100 km and the DNSxACC data product includes a measure of the thermospheric density at a similar spatial scale. These data products mean that Swarm is uniquely placed to investigate coupling between the dynamic ionosphere and the neutral atmosphere.
The Swarm-Variability of Ionospheric Plasma (Swarm-VIP) project produced statistical models of the topside ionosphere. While these models had clear successes (Wood et al., 2024; Spogli et al., 2024), a major limitation was that they did not include a measure of the thermospheric density at a similar spatial scale to the ionospheric variability observed. The Swarm Space Weather: Variability, Irregularities, and Predictive capabilities for the Dynamic ionosphere (Swarm-VIP-Dynamic) began on 2nd February 2024. One of the aims of this project is to improve the specification of the thermosphere in statistical models of ionospheric variability. Preliminary results using four years of observations from the Swarm satellites are presented. The effect on the model performance of including the thermospheric density from the DNSxACC data product is determined.

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35. Estimating core dynamics via the assimilation of magnetic field models into numerical dynamos

Dr Kyle Gwirtz[1], Weijia Kuang[1], Terence Sabaka[1]

[1]NASA GSFC, Greenbelt, MD, United States

A significant portion of the Earth's observed magnetic field is sustained by fluid motion in the planet's outer core (geodynamo) and varies over time. Records of the past magnetic field come from a variety of sources including, paleo- and archaeomagnetic data. In the modern era, satellite-based observations from missions such as SWARM, have led to a new level of spatial and temporal resolution in our knowledge of the magnetic field. Such observations of the field's secular variation (SV) can provide a unique window into the deep interior of the Earth. However, understanding the origins and implications of observed SV calls for connecting data to models of Earth's core dynamics.

Over the last 10-15 years, there has been increasing interest in using data assimilation (DA) to connect numerical dynamo simulations with magnetic field observations. DA is a general term for methods by which one can produce a "weighted combination" of numerical models and observations, to estimate a system's overall state. This approach is widely used in applications such as numerical weather prediction, where DA is used to, for example, determine initial conditions for forecasts.

We present recent work in the development of DA as a tool for understanding the Earth's deep interior, using NASA's Geomagnetic Ensemble Modeling System (GEMS). In simple terms, we "nudge" an ensemble of numerical geodynamo model runs toward observed magnetic field variations according to an Ensemble Kalman Filter (EnKF) framework. This process has the potential to recover information about dynamics which cannot be directly observed, such as the fluid flow and magnetic field deep within the interior. We highlight recently improved capabilities of GEMS, investigate its ability to constrain the core state, and discuss the impact of SWARM data on this work.

36. The Space Weather Timeline Viewer: Interactive exploration of Swarm observations with other datasets and models

Dr. Eelco Doornbos[1], Dr. Kasper van Dam[1], Dr. Timothy Kodikara[2], Drs. Mark Ter Linden[3]

[1]KNMI, De Bilt, Netherlands, [2]DLR, Neustrelitz, Germany, [3]S&T, Delft, The Netherlands

As part of the Swarm-SWITCH project, which was proposed in response to the Swarm DISC "Swarm for Space Weather" call, we have added Swarm data on the thermosphere-ionosphere to our tool for monitoring and exploring space weather observations.
The Space Weather Timeline Viewer tool is an easy-to-use open source web application. It is free to use without a need to register or install software, at https://spaceweather.knmi.nl/viewer.
The tool can show time series plots of Swarm observations in combination with a large variety of basic space weather parameters, such as ground magnetometer observations and indices, interplanetary magnetic field and solar wind conditions, etc. The intuitive interface allows users to easily zoom in on details or zoom out to view context on the timeline, by using the mouse, trackpad or touch screen in a very similar way as in online mapping applications like Google Maps.
The Swarm observations can also be shown side-by-side with models evaluated along the Swarm trajectory, which is very useful for continuous validation of data quality and model performance.
For the project, we have also added the capability to display images in the same user interface on the timeline in two distinct ways. The first method is based on sequences of images, each linked to a single timestamp. This results in movie-like playback with precise user control, useful for showing Swarm data in combination with ionospheric remote sensing data from, for example NASA GOLD and auroral imagers. The method can also be used to show Swarm observations in the context of images obtained from output of global or regional models.
The second method is based on images that contain data between two timestamps, that stretch when the user zooms in and out. This method is useful for the interactive exploration of time-latitude heat-map type plots, including keograms, but also for spectograms of high-rate observations.
In our opinion, the combination of context and detail that the tool can provide to users with these techniques will be extremely useful for space weather and space physics education, operational space weather monitoring and case studies. We will demonstrate this by showing the use of the tool in case studies on geomagnetic storms, the effects in the thermosphere-ionosphere after the January 15, 2022 volcanic eruption and the February 2022 loss of recently-launched Starlink satellites.

37. Progress on CSES/Swarm geomagnetic field modeling

Dr Yanyan Yang[1], Prof. Zhima Zeren[1], Dr Jie Wang[1], Prof. Xuhui Shen[2], CSES/Swarm Mag cal/val team

[1]National Institute Of Natural Hazards, Ministry Of Emergency Management Of China, Beijing, Beijing, China, [2]National Space Science Center, Chinese Academy of Sciences, Beijing, China

CSES has been operated for more than 6 years to continuously provide magnetic field measurements since its launch. Swarm and CSES are simultaneously in-orbit and thus provide good opportunities for joint cal/val, geomagnetic field modeling and so on. In 2019, with the cooperation of CSES/Swarm Mag cal/val team, we build a global geomagnetic field model CGGM. In recent years, we further extend our modeling work to establish types of geomagnetic field models: (1) after the correction of boom deformation for CSES FGM data and with the high latitude Swarm scalar data, we have the ability to extend CGGM model to include lithospheric field model; (2) only using the CSES scalar data, we tried to build a regional (in China) and global lithospheric model respectively, corresponding to wavelength of ~900km (for global model) and ~700km (for Chinese regional model), the result is comparable with the model obtained from Swarm data. These models show great potential of CSES magnetic field data on the updates of geomagnetic field model, especially in conjunction with Swarm mission.

38. ASM status after 10 years of operation on-board the Swarm satellites

M. Thomas Jager[1], M. François Bertrand[1], M Axel Boness[1], PhD Jean-Michel Léger[1]

[1]CEA-leti, Grenoble, France

The Absolute Scalar Magnetometers (ASM) on-board the ESA's Swarm satellites are helium-4 optically pumped magnetometers designed by CEA-Leti and developed in partnership with CNES. While the primary role of the ASM is to provide precise 1 Hz absolute scalar measurements for the vector calibration of VFM fluxgate, they are also able to deliver autonomously self-calibrated 1 Hz vector data or to provide high rate 250 Hz burst scalar data. In this presentation, we will first report on the current health status of these instruments and then review the specificities of the vector and the burst mode data provided by the ASM.

39. A new approach to modeling the time-space variations of ionospheric electric currents and magnetic fields during the September 2017 geomagnetic storm

Dr Martin Fillion[1,2], Patrick Alken[1,2], Gary Egbert[3], Astrid Maute[1,4], Gang Lu[5], Kevin Pham[5]

[1]CIRES, University of Colorado Boulder, Boulder, USA, [2]NOAA National Centers for Environmental Information, Boulder, USA, [3]College of Earth Ocean and Atmospheric Sciences, Oregon State University, , USA, [4]NOAA Space Weather Prediction Center, Boulder, USA, [5]High Altitude Observatory, National Center for Atmospheric Research, Boulder, USA

The study and modeling of Earth's ionospheric electric currents and of the associated magnetic fields is fundamental for geomagnetic field modeling, and for the study of ionosphere coupling with the neutral atmosphere and the magnetosphere. Ionospheric electric currents, which exist during both quiet and disturbed geomagnetic activity periods, can be studied using magnetic field measurements from ground magnetic observatories and satellites. Modeling these currents during geomagnetic storms is particularly challenging due to the limited data available combined with high time-space variations during such events. In this study, we propose a new approach to modeling the storm-time ionospheric electric currents and magnetic fields. The approach relies on a joint utilization of magnetic data and the physics-based Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM). The TIEGCM time-space variations are first analyzed using a toroidal-poloidal decomposition of the magnetic field. To extract a priori information on the 3D spatial structure of the ionospheric magnetic field, principal component analysis is next applied to the spherical harmonics coefficients to obtain a small number of spatial modes that represent a substantial amount of magnetic field spatial variations. Temporal variations are represented by temporal modes computed with ground observatory data following Egbert et al. (2021). The entire procedure can be carried out in the frequency domain to account for induced fields. Spatial and temporal modes can be combined to parametrized the magnetic field measured by the Swarm satellites and the model coefficients estimated by solving an inverse problem. We present preliminary results obtained with this approach for the geomagnetic storm of September 2017.

40. Swarm derived climatological model of low- and mid- latitude F-region ionospheric currents

Dr Martin Fillion[1,2,3], Gauthier Hulot[1], Patrick Alken[2,3], Arnaud Chulliat[2,3]

[1]Université Paris Cité, Institut de physique du globe de Paris, CNRS, F-75005 Paris, France, [2]CIRES, University of Colorado Boulder, Boulder, USA, [3]NOAA National Centers for Environmental Information, Boulder, USA

We present a recently published family of three empirical models of quiet-time F-region ionospheric currents and associated magnetic fields (Fillion et al., 2023). These models are derived from magnetic data acquired by the three Swarm satellites (Alpha, Bravo or Charlie) between January 1, 2016 and December 31, 2020. Each model is designed to accurately represent ionospheric currents and associated magnetic fields at low and mid latitudes. Each model fully separates spatial and climatological variations and describes the toroidal magnetic fields and the associated radial poloidal electric currents at two distinct altitudes in the ionosphere F region. Clear signatures of low- and mid-latitude interhemispheric field-aligned currents (IHFACs) are identified, and well-known climatological characteristics of these currents are reproduced. These models further provide new insights, for example on the average daily variations of IHFACs during winter in the northern hemisphere, or on variations of IHFACs with longitude. They also highlight potential driving mechanisms of these variations, such as longitudinal variations of the main field and modulation by upward propagating atmospheric tides. This opens many possibilities, such as investigating the connections between atmospheric tides and IHFACs, constraining atmospheric tides using satellite magnetic data, or more generally improving our understanding of atmosphere-ionosphere coupling. These model can also be used to investigate the connection between the magnetic fields and electric currents from the ionospheric E and F regions to both improve the separation of these fields and better understand the overall ionospheric electric current system.

All models are freely available (https://doi.org/10.18715/IPGP.2023.lddfo4s) and could easily be updated and made available as a new Swarm Level-2 product.

Fillion, M., Hulot, G., Alken, P., Chulliat, A., Modelling the climatology of low- and mid-latitude F-region ionospheric currents using the Swarm constellation, J. Geophys. Res. Space Physics, 128, e2023JA031344, doi: 10.1029/2023JA031344, 2023.

41. Novel Earth-like magnetic field morphological criteria from Modern to Pleistocene eras

Dr. Filipe Terra-nova[1], Ingo Wardinski[2], Sanja Panovska[3], Monika Korte[3]

[1]Nantes Université, Univ Angers, Le Mans Université, CNRS, Laboratoire de Planétologie et Géosciences, LPG UMR 6112, Nantes, France, [2]Institut Terre et Environnement Strasbourg, École et Observatoire des Sciences de La Terre, Université de Strasbourg, CNRS UMR 7063, Strasbourg, France, [3]GFZ German Research Centre for Geosciences, Section 2.3, Helmholtz Centre Potsdam, Potsdam, Germany

We design structural criteria to assess the robustness and the significance of spatial features from a suite of 22 different geomagnetic field models that expand several timescales. We consider both classical criteria that were used to quantify the Earth-likeness of numerical dynamo simulations (Christensen et al., 2010) as well as new proposed quantities. These include typical surface minima anomaly and polar minima magnitude as well as two criteria that quantify the impact of mantle control on the morphology of Earth's magnetic field by (i) the existence of pairs of high-latitude flux patches at each hemisphere and (ii) a polar minima North-South magnitude dichotomy. Our results show that both classical and new criteria show remarkable truncation dependency. We study the resemblance of past fields to the present-day field using their compliance to the modern era. Results shows that all models that have no transitional field (e.g. excursion and reversals) are at least 70% of their time span in excellent compliance with the modern field. This number decreases to 25% for models that have transitional field. Finally, we also provide new bounds to evaluate the Earth-likeness in numerical dynamo simulations.

42. Effective ion mass from electron density reconstruction based on LEO GNSS observations and ion density from Swarm Langmuir probes

Mr Lucas Schreiter[1,2], Andreas Brack[2], Benjamin Männel[2], Daniel Arnold[3], Adrian Jäggi[3], Harald Schuh[1,2]

[1]Technical University of Berlin, Berlin, Germany, [2]German Research Centre for Geosciences (GFZ), Potsdam, Germany, [3]University of Bern, Bern, Switzerland

In this study, a robust methodology is proposed for estimating ionospheric and plasmaspheric electron density using a network of Low Earth Orbit (LEO) satellites equipped with Global Navigation Satellite System (GNSS) receivers. The approach incorporates a Kalman Filter technique and models the logarithmic electron density through cubic B-Splines in magnetic latitude, local time, and altitude.
Performance validation involves a thorough comparison with in-situ electron density data obtained from LEO satellites at different altitude, including the Swarm mission, with careful consideration given to changes in the effective ion mass. The GNSS-derived electron density estimates serve as input for calculating the effective ion mass through Langmuir probes, providing valuable insights, particularly in periods where Swarm faceplate electron density data is unavailable. This methodology enhances our understanding of the ionospheric and plasmaspheric environment and contributes to the advancement of space-based electron density monitoring techniques.

43. Verification and validation of Swarm L1b FAST products

Mr. Ingo Michaelis[1], Dr. Martin Rother[1], Jan Rauberg[1], Dr. Guram Kervalishvili[1], Dr. Monika Korte[1]

[1]GFZ German Research Centre For Geosciences, Potsdam, Germany

The Swarm mission provides high-level data products for 10 years now. The time delay of standard operational data product (OPER) being delivered to the community is about four days. Since November 2023 ESA provides several products with a shorter lag time of only several hours (FAST) to the broad community. The idea behind the shorter lag time is the applicability for space weather monitoring and forecast. Before using the new FAST dataset, it needs to be tested to see if the FAST processing chain results in any limitations in comparison with the standard L1b processing chain. At least near real-time users need to know the limitations and opportunities of the new data products.

We compare the standard data (OPER) with the new FAST dataset. Our contribution is a verification and validation of the new FAST dataset using the standard OPER dataset as a reference. We also check the applicability of the new FAST dataset for space weather applications by simulating an operational processing that uses the FAST data as an input.

44. Core magnetic field and associated surface flow variations from 1999 to 2023

Dr Vincent Lesur[1]

[1]Université Paris Cité, Institut de physique du globe de Paris, CNRS, Paris, France

We present a recent update of the MCM series of magnetic field models and associated core surface flows. The models were derived sequentially from year 1999 to 2023, using magnetic satellite and ground observatory data. A linear Kalman filter approach and prior statistics based on numerical dynamo runs were used. The core field, the secular variation and the core surface flow models present the same characteristics as previous versions. In particular, filtering out the flow variation periods longer than ∼11.5 years leads to a filtered azimuthal flow with the same ∼7 years periodicities and patterns propagating westward by ∼60 deg longitude per year. The observed patterns are very likely related to the propagation of Magneto-Coriolis waves in the outer core.

45. LEGO model of the magnetosphere

Miss Margot Decotte[1], Karl Laundal[1], Michael Madelaire[1], Josephine Salice[1], Simon Walker[1]

[1]University Of Bergen, Bergen, Norway

Understanding the dynamic coupling between solar wind, magnetosphere, and ionosphere is crucial in space physics. We present a creative and interactive Lego model designed as a pedagogical tool to simply and visually demonstrate this complex interaction.
The solar wind influence on the magnetosphere is commonly inferred from ionospheric observations, obtained by satellites such as the Swarm mission. It can be described as the sum of a directly driven component --dayside reconnection-- and an unloading component associated with the release of magnetic energy via nightside reconnection (Laundal et al. 2020). To illustrate this concept, Akasofu (1989) identified the magnetosphere as a combination of a pitcher-type (directly driven component) and a tippy-bucket-type (unloading component) system. We have built a Lego model of Akasofu's illustration to emulate the magnetosphere--ionosphere system's mechanical behaviour. The model comprises two water-driven wheels that simulate magnetospheric dayside and nightside reconnection. Two rotating cells illustrating the ionospheric convection pattern are also included. As an additional feature, a set of LEDs replicates the aurora above the polar region.
Our model is interactive, with the ability to adjust the water input to show how the ionospheric convection and the auroral activity change in response to a varying reconnection rate (in terms of rotation speed and brightness/duration, respectively). In principle, the bucket volume and consequently the frequency at which it tips could also be adjusted to mimic the magnetosphere-ionosphere coupling on other planets.
Our Lego model has been thought of as a versatile and engaging tool for illustrating magnetospheric dynamics, making it a valuable asset in space physics education.

46. Comparison of scalar magnetic field data of China Seismo-Electromagnetic, Macao Science and Swarm satellites

Master Alexander Betzler[1], Roland Lammegger[2], Andreas Pollinger[1], Christoph Amtmann[2], Irmgard Jernej[1], Martìn Agú[1], Bingjun Chen[3], Bin Zhou[3], Zeren Zhima[4], Yang Yanyan[4], Tielong Zhang[1,5], Mingyu Wu[5], Keke Zhang[6], Yi Jiang[6], Werner Magnes[1]

[1]Space Research Institute, Austrian Academy of Sciences, Graz, Austria, [2]Institute of Experimental Physics, Graz University of Technology, Graz, Austria, [3]National Space Science Center, Chinese Academy of Sciences, [4]National Institute of Natural Hazards, Ministry of Emergency Management of China, [5]Institute of Space Science and Applied Technology, Harbin Institute of Technology Shenzhen, [6]Macau Institute of Space Technology and Application, Macau University of Science and Technology

The Coupled Dart States Magnetometer (CDSM) is a quantum-optical, scalar magnetometer, whose sensor and near sensor electronics have been developed by the Austrian Space Research Institute in close cooperation with the University of Technology Graz. It has been successfully launched on the China Seismo-Electromagnetic Satellite 1 (CSES 1) in February 2018 and Macao Science Satellite 1 (MSS 1) in May 2023. The former is on a polar, sun-synchronous, low Earth orbit with an altitude of about 500km while the latter has a nearly circular orbit with an inclination of 41 degree and an altitude of about 450km.
We compare the scalar magnetic field data of both CDSMs to the scalar data on the Swarm satellites. A special emphasis is placed on the times the satellites are close to each other with a distance of less than 1000 km, as it allows us to correlate the measurements in a straightforward manner.

47. The great potentiality of low earth orbiting satellite missions such as Swarm for detecting pre-earthquake ionospheric anomalies

Prof. Angelo De Santis[1], Dr Saioa Campuzano[1,2], Massimo Calcara[1], Gianfranco Cianchini[1], Serena D'Arcangelo[1,2], Mariagrazia De Caro[1], Cristiano Fidani[1], Adriano Nardi[1], Martina Orlando[1], Loredana Perrone[1], Alessandro Piscini[1], Dario Sabbagh[1], Maurizio Soldani[1]

[1]Istituto Nazionale di Geofisica e Vulcanologia -INGV, Rome, Italy, [2]Universidad Complutense de Madrid - UCM, Madrid, Spain

Sometimes, satellites designed for specific objectives, therefore equipped with appropriate payloads, extend their field of application to scientific areas very distant from the original ones. This is the case of the low earth orbiting ESA Swarm mission: initially designed with its original configuration (three identical satellites equipped with magnetometers, Langmuir probes, high-energy particle detectors, GPS, etc.) to monitor and study the geomagnetic field and the state of the ionosphere and magnetosphere, the same data could be analyzed to investigate pre-earthquake ionospheric anomalies. For the first time, in 2017, a study (De Santis et al., 2017; https://doi.org/10.1016/j.epsl.2016.12.037) showed some pre- and post-earthquake magnetic field anomalies detected by the Swarm satellites on occasion of the 2015 Nepal M7.8 earthquake. Interestingly, the cumulative number of satellite anomalies and the cumulative number of earthquakes behaved similarly with the so-called S-shape, providing an empirical proof on the lithospheric origin of the satellite anomalies and supporting a lithosphere-atmosphere-ionosphere coupling (LAIC). Following the same approach, other promising results were obtained for 12 case studies in the range of 6.1-8.3 earthquake magnitude, in the framework of the SAFE (SwArm For Earthquake study) project funded by ESA (De Santis et al., 2019a; https://doi.org/10.3390/atmos10070371). In 2019, almost five years of Swarm magnetic field and electron density data were analyzed with a Superposed Epoch and Space approach and correlated with major worldwide M5.5+ earthquakes (De Santis et al., 2019b; https://doi.org/10.1038/s41598-019-56599-1). The analysis verified a significant correlation between satellite anomalies and earthquakes above any reasonable doubt, after a statistical comparison with random simulations of anomalies. The work also confirmed the empirical Rikitake law (1987), initially proposed for ground data: the larger the magnitude of the impending earthquake, the longer the precursor time of anomaly occurrence in the ionosphere from satellite. A more recent investigation (Marchetti et al., 2022; https://doi.org/10.3390/rs1411264) over a longer time series of Swarm data, i.e. 8 years, confirmed the same results. Furthermore, we demonstrated through several case studies (e.g. Akhoondzadeh et al., 2019; https://doi.org/10.1016/j.asr.2019.03.020; De Santis et al., 2020; https://doi.org/10.3389/feart.2020.540398; De Santis et al., 2022; https://doi.org/10.1016/j.rse.2022.113325; Akhoondzadeh et al., 2022; https://doi.org/10.3389/feart.2022.820189) that the integration with other kinds of measurements from ground, atmosphere and space (e.g. CSES data) reveals a chain of processes before mainshocks of many seismic sequences. We finally propose a two-way model including a diffusion process in the lithosphere with almost direct (likely e.m.) coupling with the above atmosphere and ionosphere and another with a delayed LAIC to explain most of the found anomalies preceding large earthquakes.

48. Latest Investigations into dB_Sun Disturbance

Mr Lars Tøffner-Clausen[1], Prof Peter Brauer[1]

[1]DTU, Kgs Lyngby, Denmark

Recent investigations of the Sun driven magnetic disturbance, dB_Sun, on the Swarm satellites have shed some more light on features which were previously poorly understood. We will present results of the investigations as well as potential root cause of the observed effects.

49. Performance Assessment for Statistical Models of the Ionospheric Variability in the Topside Ionosphere

Dr. Yaqi Jin[1], Dr. Luca Spogli, Dr. Jaroslav Urbář, Dr. Alan Wood, Elizabeth Donegan-Lawley, Lasse Clausen, Golnaz Shahtahmassebi, Lucilla Alfonsi, James Rawlings, Antonio Cicone, Daria Kotova, Claudio Cesaroni, Per Høeg, Gareth Dorrian, Luke Nugent, Sean Elvidge, David Themens, María Aragón, Pawel Wojtkiewicz, Wojciech Miloch

[1]University Of Oslo, Oslo, Norway

Statistical models of the variability of plasma in the topside ionosphere based on the Swarm data have been developed in the “Swarm Variability of Ionospheric Plasma” (Swarm-VIP) project within the European Space Agency's Swarm+4D-Ionosphere framework. The models can predict the electron density, its gradients for three horizontal spatial scales – 20, 50 and 100 km – along the satellite track and the level of the density fluctuations. Despite being developed by leveraging on Swarm data, the models provide predictions that are independent of these data, having a global coverage, fed by various parameters and proxies of the helio-geophysical conditions. Those features make the Swarm-VIP models useful for various purposes, which includes the possible support for already available ionospheric models and to proxy the effect of ionospheric irregularities of the medium scales that affect the signals emitted by Global Navigation Satellite Systems (GNSS). The formulation, optimisation and validation of the Swarm-VIP models are reported in Wood et al. (2024). In the present work, we describe the performance assessment of the models, by addressing their capability in reproducing the known climatological variability of the modelled quantities, and the ionospheric weather as depicted by ground-based GNSS receivers, as a proxy for the ionospheric effect on GNSS signals. Additionally, we demonstrate that, under certain conditions, the model can better reproduce the ionospheric variability than a physics-based model.

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50. The extended Dedicated Lithospheric field model (xDLFI) and its interpretation in terms of global magnetic crustal thickness

Dr Erwan Thebault[1], Gauthier Hulot[2]

[1]Observatoire de Physique du Globe de Clermont-Ferrand / OPGC, Aubiere , France, [2]Université Paris Cité, Institut de Physique du Globe de Paris, CNRS, F-75005 Paris, France, Paris, France

Detailed mapping of the Earth's magnetic field brings key constraints on the composition, dynamics, and history of the crust. Satellite and near-surface measurements detect different length scales. We build a CHAMP and Swarm satellite dataset and combine it with the World Digital Magnetic Anomaly Map: version 2.1 (Dyment et al., IUGG Berlin, 2023), the most globally complete grid of airborne and marine scalar anomaly data. We then derive a lithospheric magnetic field model in Spherical Harmonics to degree 1500. Recovering such a high degree expansion requires estimating 2,253,000 parameters, which can hardly be achieved through a single global inversion. Therefore, we follow a regional approach that allows us to perform a series of independent regional linear inverse problems using robust parallel procedures, to deal regionally with the Backus effect in equatorial regions, and to assess independently each regional model. The series of regional model is then transformed into standard Spherical Harmonics by fast spherical transform. The general protocol is given in Thébault et al. "A Spherical Harmonic Model of Earth's Lithospheric Magnetic Field up to Degree 1050." Geophysical Research Letters 48.21 (2021): e2021GL095147) and was updated for this study to account for the most recent SWARM data and the updated WDMAM 2.1 near surface compilation. We then interpret the lithospheric magnetic field model in terms of magnetic crustal thickness for the large scales. Our strategy, which relies solely on magnetic field measurements and statistical properties of the crustal magnetic field, differs considerably from previous studies in which large spatial scales down to about 2500 km are constrained by global Moho depth models. Here, we process the SH lithospheric magnetic field model in both the spectral and the geographical domains without seismic a priori information. Preliminary results confirm that statistically the Moho depth is a magnetic boundary for the large magnetic spatial scales.

51. Studying time-correlated errors derived from Swarm vector residuals to improve uncertainty estimates of geomagnetic field models

Mr Clemens Kloss[1], Christopher C. Finlay[1], Nils Olsen[1], Lars Tøffner-Clausen[1]

[1]Technical University Of Denmark, Kgs. Lyngby, Denmark

Modern geomagnetic field models can successfully represent many details of the observed large-scale field and its slow time changes. However, a lack of realistic model uncertainty estimates hinders their use in applications such as assimilation into numerical Geodynamo simulations. During the model estimation, data errors are usually assumed to be temporally uncorrelated and are often specified independent of position. However, limitations of the model parameterization lead to residuals between model predictions and magnetic observations that are not only larger than the expected measurement noise but also time-correlated and varying with position.

Here, we study the spatiotemporal statistics of the vector residuals between magnetic observations from the Swarm satellites and predictions from the CHAOS-7 field model. We compute sample covariances from the vector residuals as a function of time lag for different quasi-dipole latitudes and magnetic local times. We find that these covariances can be significant, particularly at mid-to-high latitudes.

By fitting simple spatiotemporal covariance functions to the quiet-time night-side features in the empirical covariances, we explore ways to build realistic data error matrices for geomagnetic field modeling. We present preliminary results from test models estimated within the CHAOS modeling framework, illustrating the effect of correlated data errors on the associated field model uncertainties.

52. The role of the Swarm mission in advancing our understanding of Earth's core dynamics

Dr Julien Aubert[1], Dr Philip Livermore[2], Dr Christopher Finlay[3], Dr Alexandre Fournier[1], Dr Nicolas Gillet[4]

[1]IPG Paris, Paris, France, [2]University of Leeds, Leeds, United Kingdom, [3]DTU Space, Copenhaguen, Denmark, [4]IsTerre, Grenoble, France

Swarm has stimulated the development of new numerical models able to render and explain the observed rapid variations of Earth's internal magnetic field. Here we present example results obtained within the SWARM+4D DEEP EARTH: CORE project funded by ESA.

Explaining the rapid core field signals captured by Swarm required models of Earth's core dynamics and the geodynamo to reach the strong-field dynamical regime, where the magnetic energy strongly exceeds the kinetic energy. In this regime, hydromagnetic waves with interannual periods evolve over a slowly evolving background state driven by convection in Earth's outer core. Our work has therefore first focused on the numerical reproduction and characterisation of these waves, and the demonstration of their success in accounting for the observed geomagnetic variations. In a second step, assimilation of the Swarm data into numerical models operating in the strong-field regime has enabled the estimation of a reference dynamical background state relevant for the present-day Earth's core.

Through this framework, the observations provided by Swarm can help to improve our understanding of core dynamics over time scales extending beyond the range of the mission. To illustrate this perspective, we will discuss the long-term dynamical balance underlying the South Atlantic low magnetic intensity anomaly, and its possible evolution during the past millennia.

53. Estimating tidal transports from geomagnetic satellite observations

M.sc. Aaron Hornschild[1], Dr. Jan Saynisch-Wagner[1], Dr. Julien Baerenzung[1], Prof. Dr. Maik Thomas[1]

[1]GFZ German Research Center For Geosciences, Potsdam, Germany

The tidal movement of conductive seawater through Earth's magnetic field induces secondary electromagnetic signals. For twenty years, these tidal magnetic signals have been detectable in satellite magnetometer observations, such as Swarm or CHAMP.

In contrast to tidal elevations, which can easily be measured by satellite altimetry, the tidal transports are more difficult to observe. Here, we demonstrate how global tidal transports can be directly derived from satellite magnetometer observations.

We estimate the ocean tidal transports based on CHAMP and Swarm satellite magnetometer observations by using a Kalman-Filter with statistical forecast components. The magnetometer observations are separated into several magnetic sources, e.g., core field, lithospheric field, ionospheric field, and magnetic oceanic tidal signals. With the exception of the tidal component, the spatio-temporal evolution of these magnetic field components are prescribed by parameterized autoregressive processes. For the separation, the magnetic tidal signals are modelled as harmonic oscillations and inverted into tidal transports.

This approach requires only very loose assumptions from numerical forward models and provides, for the first time, an estimate of tidal transport from satellite magnetometer observations. We present the resulting tidal transport fields, compare them with altimetry based tidal transports, and discuss the posterior errors.

54. Determining the dynamics at the core mantle boundary using Physics-Informed Machine Learning

Miss Naomi Shakespeare-Rees[1], Professor Phillip Livermore[1], Professor Christopher Davies[1], Dr Ciarán Beggan[2], Dr William Brown[2], Professor Chris Finlay[3]

[1]University Of Leeds, Leeds, United Kingdom, [2]British Geological Survey, Edinburgh, UK, [3]DTU Space, Technical University of Denmark, Kongens Lyngby, Denmark

The Earth’s geomagnetic field arises from the constant motion of the fluid outer core. By assuming that these motions are advection-dominated, rather than diffusion, one can relate this motion at the core surface to the secular variation of the geomagnetic field, providing an observational approach to understanding the motions in the deep earth. Existing methods predominantly employ global inversions, assuming large-scale solutions where all observed secular variations are attributed to the flow. In contrast, this work introduces a novel technique based Physics-Informed Neural Networks, to perform local flow inversions at the core-mantle boundary from the CHAOS-7 model, a global field model incorporating data from the Swarm mission. Our approach incorporates a loss function comprising of both data loss and physics-based loss, in which different flow assumptions can be swapped in and out when needed. This talk presents the set-up, underlying assumptions, and preliminary results of this methodology using Toroidal and Tangentially Geostrophic flow constraints, as well as show a comparison of flow features from our local inversions with global ones. Furthermore, we discuss the technical and scientific next steps to advance this method as a powerful tool in understanding the dynamics of the Earth's core.

55. The role of magnetic fields as measured by Swarm as fingerprints of processes in the terrestrial lithosphere

Dr. Michael Purucker[1]

[1]Nasa, Greenbelt, United States

The Swarm mission has contributed to the highest SHD models of the lithosphere to date (eg: LCS-1, Olsen et al). These models demonstrate that many processes can generate magnetic fields that can be sampled by the Swarm constellation, and more processes can be included if we extend the wavelength range with the WDMAM series maps. A short list of those processes might include subduction & serpentinization, heat flux, tectonics, insolation, rheology, basin development, and impact. The subduction signature associated with serpentinization was recognized from the earliest POGO and MAGSAT observations in the 1970s (Frey, 1982) and continues to be delineated by Swarm. During subduction the iron-rich silicates that are being returned to the mantle in the presence of water and pressure react to form serpentine + magnetite + hydrogen. The hydrogen is a potential energy resource, and magnetic fields can be used to prospect for it (Milkov, 2022). The talk will focus on recent discoveries of processes, and how Swarm can deepen our understanding of them.

56. Swarm Fast data processing chain

Ms Roberta Forte[1], Nicola Comparetti[1], Enkelejda Qamili[1], Lars Tøffner-Clausen[2], Stephan Buchert[3], Christian Siemes[4], Anna Mizerska[5], Alessandro Maltese[1], Jonas Bregnhøj Nielsen[2], Thomas Nilsson[3], Maria Eugenia Mazzocato[1], María José Brazal Aragón[5], Florian Partous[5], Đorđe Stevanovic[5], Giuseppe Albini[6], Antonio De la Fuente[7], Anja Stromme[7]

[1]Serco for ESA, Frascati, Italy, [2]DTU Space, Copenhagen, Denmark, [3]Swedish Institute of Space Physics, Uppsala, Sweden, [4]TU Delft, Delft, The Netherlands, [5]GMV Poland, Warsaw, Poland, [6]ESA ESOC, Darmstadt, Germany, [7]ESA ESRIN, Frascati, Italy

After 10 years in Space, Swarm ESA's Earth Explorer mission is still in excellent shape and continues to contribute to a wide range of scientific studies, from the core of our planet, via the mantle and the lithosphere, to the ionosphere and interactions with Solar wind.
Its highly accurate observations of electromagnetic and atmospheric parameters of the near-Earth space environment, and the peculiar mission constellation design, make Swarm eligible for developing novel Space Weather products and applications.
In April 2023 a "Fast" processing chain has been transferred to operations, providing Swarm L1B products with a minimum delay respect to the acquisition. These Fast data products add significant value in monitoring present Space Weather phenomena and help modelling and nowcasting the evolution of several geomagnetic and ionospheric events.
This work presents the set-up of the Swarm "Fast" data processing chain, current status and plans for future improvements and applications.

57. A new magnetic compilation of Greenland from airborne and satellite data by using equivalent source modeling and spherical harmonic expansion

Dr. Björn Heincke[1], Wolfgang Szwilius[2], Judith Freienstein[2], Jörg Ebbing[2]

[1]Geus, Copenhagen, Denmark, [2]Kiel University, Kiel, Germany

In remote inaccessible Artic regions such as the largely ice-covered Greenland, magnetic compilations are considered as an essential source for obtaining information about the lithospheric structure and are relevant for various geological applications (as e.g., understanding tectonic history, plate reconstruction. heat flow mapping, regional geological mapping, mineral and hydrocarbon exploration). The last magnetic compilation covering all of Greenland is the CAMP-M compilation (Gaina et al., 2011), created in 2011. Since then, a significant number of new aeromagnetic surveys have become available as well as the magnetic satellite data from the SWARM mission. These previous compilations were, furthermore, created by conventional methodologies where magnetic grids from aeromagnetic datasets were simply merged and long-wavelength components from satellite data were typically included through some form of Fourier-transform based filtering. Such approaches have several disadvantages: (1) they have limited ability to properly combine aeromagnetic datasets with different data quality, data density and flight altitude, (2) have difficulties identifying erroneous data points, (3) are not suitable to present the grid with a flexible resolution associated with varying data coverage and (4) ignore the influence of the Earth's spherical shape on the long-wavelength components.

Therefore, the development of a new magnetic compilation from Greenland was initiated as part of the ESA project GOCE+Greenland in 2021, where a more advanced methodology was used that combines equivalent source modelling and a spherical harmonic expansion. This contribution presents the magnetic compilation, but a second contribution to the Swarm 10 Year Anniversary & Science Conference (Szwillus et al., 2024) focusses on the methodological aspects.

The here presented total magnetic intensity anomaly map comprises southern and central Greenland and is the first version of a larger compilation that will be stepwise extended to cover whole Greenland including the Inland Ice and the adjacent shelf regions. It is built out of all accessible modern regional aeromagnetic surveys from Greenland but also uses older datasets without GPS positioning in areas where modern data are lacking. Magnetic data are currently taken from the surveys of the projects AEROMAG and AEM (Rasmussen et al., 2013), GICAS (Thorning et al., 1988), EASTMAR (Larsen & Thorning, 1980), ICEBRIDGE and GAP91/92 (Brozena, 1992), and from offshore datasets acquired by the company TGS-NOPEC. Since long wavelength components in aeromagnetic data are often considered as unreliable, they are replaced by the ones from the LCS-1 satellite model (Olsen er al., 2017) that are derived from magnetic gradient measurements of SWARM and CHAMP missions.

In the equivalent source modelling approach, the datapoints from the aeromagnetic surveys (at their measuring locations) are used as input data in an inversion to determine the apparent susceptibilities of magnetic dipoles that are arranged in three uniform grids with different source spacing and depths (coarsest spacing: 10 x 10 km; finest spacing: 0.7 x 0.7 km). The presented total magnetic intensity map is simulated from the dipole responses at a constant height of 2000 m asl and with a grid spacing of 700 x 700 m. Regularizations in the inversion for the different equivalent source grids are chosen such that the resulting resolution is flexible and adapted to the largely varying magnetic data coverage in Greenland. In a last step satellite data are incorporated in the compilation, by expressing the responses from the individual equivalent dipole sources in spherical harmonics (see Dilixiati et al., 2022) and replacing the long-wavelengths associated with Gaussian coefficients of degrees n=13-133 with the ones from LCS-1 satellite data. The approach is described in more detail by Szwillus et al., 2024.

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58. Swarm instruments, processors and data quality after 10 years in Space

Mr Nicola Comparetti[1], Roberta Forte[1], Enkelejda Qamili[1], Lars Tøffner-Clausen[2], Stephan Buchert[3], Johnathan Burchill[4], Christian Siemes[5], Anna Mizerska[6], Jonas Bregnhøj Nielsen[2], Thomas Nilsson[3], Alessandro Maltese[1], Maria Eugenia Mazzocato[1], Đorđe Stevanovic[6], Florian Partous[6], María José Brazal Aragón[6], Lorenzo Trenchi[1], Elisabetta Iorfida[7], Irene Cerro Herrero[7], Berta Hoyos Ortega[7], Antonio De la Fuente[8], Anja Stromme[8]

[1]Serco for ESA, Frascati, Italy, [2]DTU Space, Copenhagen, Denmark, [3]Swedish Institute of Space Physics, Uppsala, Sweden, [4]University of Calgary, Calgary, Canada, [5]TU Delft, Delft, The Netherlands, [6]GMV Poland, Warsaw, Poland, [7]European Space Agency - ESTEC, Noordwijk, The Netherlands, [8]European Space Agency - ESRIN, Frascati, Italy

On 22nd November 2023 ESA Swarm mission celebrated 10 years in Space, characterizing Earth's geomagnetic, ionospheric and electric fields, for a better understanding of our planet's interior and its environment. After a decade in orbit, the mission achieved remarkable scientific results, opening the door for many innovating applications largely beyond its original scope. Moreover, the processing algorithms have been continuously improved since the beginning of the mission, to cope with the evolving needs of the scientific community, and to keep providing excellent quality data and processing performances.
This work provides an overview of the Swarm constellation status, with a focus on the improvements introduced in data processing chain, instruments performances, upcoming evolutions, together with other innovative Swarm-based data products and services.

59. Total square-Root Electron Content (TREC): Sounding the Ionosphere with ELF Whistlers Detected by the Swarm Mission

Mr Martin Jenner[1], Pierdavide Coïsson[1], Gauthier Hulot[1], Dalia Buresova[2], Louis Chauvet[1], Vladimir Truhlik[2]

[1]Université Paris Cité, Institut de physique du globe de Paris, CNRS, F-75005, Paris, France, [2]Institute of Atmospheric Physics of the Czech Academy of Sciences, Prague, Czechia

Powerful lightning strikes generate broadband electromagnetic signals. At Extremely Low Frequencies (ELF), the signal partly leaks into the ionosphere and produces whistlers that can be detected by satellites. Indeed, the satellites Alpha (~450 km) and Bravo (~510 km) of the Swarm mission can detect those signals during 250 Hz burst-mode acquisition campaigns of their Absolute Scalar Magnetometers (ASM). The time of propagation of these whistlers depends on their propagation path and the distribution of ionization in the ionosphere crossed along that path. Under the cold plasma assumption and within the ELF band, we led a theoretical development to study the propagation of such waves in the ionosphere. It suggests a proportionality relationship between the group delay of the whistler and the integral of the square root of the electron density along the propagation path of the wave. We name this quantity the Total square Root Electron Content (TREC).

An a priori estimation of the propagation path is obtained with ray tracing through an ionosphere based on the International Reference Ionosphere 2016 (IRI), in a dipolar magnetic field derived from the IGRF-13. In conjunction with the whistler analysis from the Swarm data, we are able to calculate the TREC for any whistler along its propagation path.

This method has been tested on 378 whistlers that occurred between April 2020 and December 2022, within 500 km of one of three active ionosondes in the American sector: Ramey, Boa-Vista and Santa-Maria. Swarm TREC have been compared against predicted TREC computed by integration of the ionospheric profiles from climatological IRI and from experimental ionosondes. A topside correction was applied for the latter, taking advantage of in-situ measurements of the plasma density by the Swarm Langmuir probes. The Swarm-derived TREC is well correlated with the predicted TREC, validating the possibility of obtaining new ionospheric measurements from whistler parameters.

As an example of possible applications, the TREC measured on longitudinal streaks of whistlers is used to investigate ionospheric structures. These are of particular interest in regions with limited GNSS-TEC coverage. The potential uses of the TREC and its recovery method will be discussed.

60. VirES for Swarm & Virtual Research Environment: Serving Swarm data, models, and tools

Mr. Martin Pačes[1], Dr. Ashley Smith[2]

[1]EOX IT Services, GmbH, Wien, Austria, [2]University of Edinburgh, Edinburgh, United Kingdom

The VirES service can be described as an ecosystem: the VirES server provides robust API-based access to both data and models derived from Swarm measurements; the VirES web interface provides visual point-and-click access [1]; the viresclient Python package provides the basis for a programmatic workflow and connection to the scientific Python landscape [2]; the Virtual Research Environment (VRE) provides a ready-to-code Jupyter environment to empower researchers to quickly start writing and running code using the latest Python packages [3].

In tandem with the evolution of the Swarm product portfolio, VirES evolves to provide access to and visualisation of new data products as they are published. The most recent addition are the Swarm FAST L1B products.

Beyond provisioning of the static data products, Swarm activities are shifting toward on-demand processing and tools. We support development and dissemination of such tools in a scientist-led way through the VRE. These take the form of both computational notebooks and of Python packages.

With a growing number of data sources, both Earth-bound and orbital, it is critical to enable easier multi-dataset scientific workflows. At the same time, there is a multiplicity of research software projects, complex to navigate and make use of. We are tackling these issues through adoption of the Heliophysics API specification (HAPI [4, 5]), and coordination with the Python in Heliophysics Community.

[1] https://vires.services
[2] https://viresclient.readthedocs.io
[3] https://notebooks.vires.services
[4] https://hapi-server.org
[5] https://vires.services/hapi

61. Adding high energy particle mapping to the Swarm observations suite

Prof. John Jørgensen[1], Dr. Troelz Denver, Dr. Matija Herceg, Dr. Julia Sushkova, Dr. Mathias Benn, DR. Peter Jørgensen, Dr. Anja Stromme

[1]DTU-Space, Kgs. Lyngby, Denmark

The radiation belts of Earth are important physical effects, affects a wide range of physical systems, spaceflight and mundane human activities, directly or indirectly. E.g. a large part of the Earth Space Weather is driven by radiation belt dynamics. Mapping and modeling these radiation belts and their dynamics, is thus important if to understand, mitigate and ultimately create early warning systems.

The Swarm space segments, designed and optimized as geomagnetic mapping observatories, are formally carrying energy particle instrumentation for lower energies. However, the star trackers onboard, the ASC', are sensitive to high-energy particles, and, since the ASC', to deliver high accuracy attitude for the satellites, must detect and compensate for the impact of such particles in real time. To perform the high-energy particle signature suppression, these must be identified, isolated and tracked. Consequently, the high-energy particle flux constantly monitored by the Swarm satellites with high time resolution. In 2023, after a thorough energy and flux-transport calibration process, these observations became formally available to the science community, by ESA, formally turning the Swarm satellites into high-energy particle monitors.

In this talk, we present the methodology, calibration and data format of this new suite of observations. We present energy and flux ranges of the new observables and discuss their resolution and accuracy for local and global mapping. With the South Atlantic anomaly as an example, we show the high time and flux coverage. From these we present observed phenomena such the east-west asymmetry, and, how these observations leads to a model of drift-shell stability and inwards particle diffusion/transport in connection with solar storms/CME.

62. Crustal magnetic field modelling to spherical harmonic degree 2000

Dr Callum Watson[1], Will Brown[1], Natalia Gomez Perez[1], Ciarán Beggan[1], Michael Bareford[2]

[1]British Geological Survey, Edinburgh, United Kingdom, [2]Edinburgh Parallel Computing Centre, University of Edinburgh, Edinburgh, United Kingdom

Earth's crust provides a significant component of the geomagnetic field, which has large variation over short distances, but has negligible variation in time. Whether for precise direction seeking or geological surveying, this crustal field has a considerable human impact. The fine spatial scales involved mean that satellite data can only resolve longer-wavelength features, while the lack of time variation means that data accumulates over time. One of the key repositories of this collated data is the World Digital Magnetic Anomaly Map (WDMAM), produced by an international task force.

In order to make use of this predominantly scalar data to obtain the full field at arbitrary locations, the British Geological Survey (BGS) produce a spherical harmonic model based on this data. Since 2019 this model has extended to spherical harmonic degree 1440, corresponding to a minimum wavelength of around 28 km.

In 2023, an updated version of WDMAM was released, providing greater detail in many parts of the world. This coincides with an overhaul of the BGS crustal modelling code that has resulted in improved computational performance and the feasibility of computing very high resolution models. We thus evaluate the potential of a renewed crustal model up to degree 2000 (minimum wavelength around 20 km), and the inclusion of updated WDMAM data.

63. Not Swarm - a reassessment of possibilities with a lower quality mission

Dr. Richard Holme[1], Mr. Isaac Salt[1]

[1]University Of Liverpool, West Kirby, United Kingdom

Swarm and its predecessors CHAMP and Oersted have been enormously successful in improving our understanding of the Geomagnetic field. However, in this presentation we consider a possible future in which new missions of similar quality are not necessarily forthcoming. As an example, we consider data from the CSES satellite, focusing primarily on absolute intensity data only. Using only such data leads to the well-known of (if now perhaps less well known) Backus effect - the error arising from unmodelled fields perpendicular to the main field. It has been shown that knowledge of the magnetic equator alone can resolve formal non-uniqueness - we investigate practical implications of constraint of this feature using dayside intensity data from the same satellite. For the CSES satellite data above 60 degrees latitude is very limited - we examine the additional implications of this for Backus effect errors. We consider simple models of the external field, and also assumption that crustal field does not vary significantly with time, to see whether such modelling produces better quality modelled (as measured against vector data models such as Chaos). Finally, we examine the influence of additional data (particularly from magnetic observatories). Overall, we constrain to what extent we will be able to model time-varying main field in an uncertain future.

64. Geomagnetic Virtual Observatories: 10 years of Swarm, 25 years of GVO

Dr. William Brown[1], Dr. Natalia Gomez-Perez[1], Dr. Callum Watson[1], Dr. Ciarán Beggan[1]

[1]British Geological Survey, Edinburgh, United Kingdom

We now have available 25 years' worth of satellite observations suitable for producing Geomagnetic Virtual Observatories (GVO). GVO are a method for distilling scattered satellite observations into point estimates approximating the field in a region of time and space, to produce time-series akin to those from ground observatories. They allow the observation of secular variation (SV), which otherwise requires the construction of a field model to obtain from satellite data.

The geomagnetic observations come from a variety of satellite missions: dedicated geomagnetism satellites Ørsted and CHAMP; a dedicated geomagnetism constellation, Swarm; platform magnetometers on CryoSat-2; constellations of platform magnetometers on Iridium; and a dedicated geomagnetism cubesat, MSS-1. In the coming years we expect to be able to produce GVO from more geomagnetic cubesat missions, and potentially from other new or existing satellites.

Each type of satellite mission brings a new set of characteristics to the data, and thus the GVO that can be created from them. We investigate the separation of core field signals from GVO from different satellite missions. We assess the approach to producing GVO for satellites with inclined orbits (e.g. MSS-1, the proposed NanoMagSat), as opposed to the so far typical near-polar orbits (e.g. CHAMP, Swarm). A particular focus is given to how local-time sampling of the satellite impacts GVO; we use Principal Component Analysis (PCA) to extract local-time dependent signals from GVO and consider the best GVO design considerations to mitigate such effects.

65. Detecting Waves in Core Surface Flow Acceleration Derived from 26 Years of Secular Variation

Ms. Carla Grune[1], Prof. Kathy Whaler[1], Mr. Frederik Madsen[1]

[1]University Of Edinburgh, Edinburgh, United Kingdom

Fluid motion in the liquid outer core of the Earth produces major parts of the Earth's magnetic field, and its time changes over timescales of one year or longer, the secular variation. Thus, it is possible to infer estimates of the fluid flow from observations of the field and the secular variation.
Data from the Swarm mission are combined with data obtained from the previous Ørsted, CHAMP, and CryoSat-2 missions to yield a secular variation dataset spanning almost 26 years, from late 1997 to early 2023. The data are represented by geomagnetic virtual observatory (GVO) time series at 4-month intervals. At the beginning, end, and in a gap in the middle, the satellite dataset is furthermore supplemented with in total 3 years of ground observatory data.

These secular variation data were inverted for velocity profiles of the fluid flow at the core-mantle boundary assuming it is purely advective, with the main field specified by the CHAOS-7.16 field model. The inversion is regularized both in time and in space: In time, the differences in velocity between individual epochs were minimized, that is, the acceleration. In space, small-scale velocity structures are penalized by using the "strong norm".

From the obtained velocities, flow acceleration is calculated by taking the first differences of the velocities at successive epochs. The acceleration data are detrended in time, here, the effect of removing different detrending functions from the data is investigated.

Time-longitude plots show alternating positive and negative, and sloping, features in the azimuthal acceleration at low latitudes, interpreted as standing waves and propagating waves, respectively. On the time-longitude plots, waves propagating both eastwards and westwards were observed, with propagation velocities of the order of 1000 km/yr which is in agreement with previous inferences of fast core waves. Power spectral density plots additionally reveal that there is a higher energy content in the westward propagating waves than in those travelling eastwards. These plots were further used to determine the wavenumbers and frequencies of the dominant periodic features, from these, more precise estimates of the wave propagation velocities were calculated.

66. On the occurrence of unusual ELF signals in Swarm ASM burst mode data

Mr. Adam Emsley[1], Dr. Ciaran Beggan[1], Dr. Kathy Whaler[2]

[1]British Geological Survey, Edinburgh, United Kingdom, [2]University of Edinburgh, Edinburgh, United Kingdom

Scalar magnetometers onboard each Swarm satellite operate under a 50 Hz acquisition mode, thus probing ionospheric signals up to 25 Hz. An additional experimental 250 Hz burst-mode is also periodically switched on, allowing signals up to 125 Hz to be investigated. Through analysing burst-mode data in the frequency-time domain, graphing the data as spectrograms, we find both manmade and geophysical signals. Known features, such as auroral hiss and plasma bubbles, produce broad incoherent signatures, and powerline harmonic radiation is observed as stable 50/60 Hz lines. Linear and quadratic signals contaminate the data without an obvious temporal or spatial trend; however, their origin is suspected to be instrumental interference.

Notably we find hook-like features in the frequency band 80-125 Hz, persisting for 1-5 minutes and consistently occurring orbit-on-orbit during magnetic local times (MLT) 0900 and 1500. These signals are confined to low-mid latitudes, occurring over the equatorial ionisation anomaly, though in recent data are found to also extend into higher latitudes. 'Hooks' occur during periods of heightened solar activity and have only been found in data from 2014 and 2022-2023. Thus far it seems a critical plasma density is not required; however, irregularities in plasma density data, recorded at 2 Hz cadence, are seen to occur when the signals are visibly modulated. The plasma density gradient has the same 0900/1500 MLT trend, with strong small-scale perturbations, as well as a seasonal hemisphere and solar cycle bias.

Ground observatory data from Taiwan and Antarctica reveal similar hook-like signals in the frequency band 60-100Hz, attributed to lightning-induced whistlers. These observations bear the same 0900/1500 MLT bias as Swarm data, though also show occurrences around 2000 MLT. This MLT bias suggests that hooks in Swarm data may be related to lightning, with the MLT trend reflecting peaks in Schumann resonance intensity as lightning energy resonates within the Earth-Ionosphere cavity. We suggest that hooks are produced by a geophysical mechanism and are possibly caused by one, or a combination of, small-scale plasma bubbles induced by solar activity and lightning-generated energy.

67. Advances in research of equatorial plasma depletions enabled by the Swarm missions

Dr. Claudia Stolle[1], Dr. Juan Rodríguez-Zuluaga[2], Dr. Chao Xiong[3], Dr. Tarique A. Siddiqui[1], Dr. Suman K. Das[1], Dr. Lucas F. Schreiter[4,5], Dr. Jaeheung Park[6], Dr. Hermann Lühr[5], Dr. Yosuke Yamazaki[1], Dr. Guram Kervalishvili[5], Jan Rauberg[5]

[1]Leibniz Institute of Atmospheric Physics at the University of Rostock, Kühlungsborn, Germany, [2]Johns Hopkins University Applied Physics Laboratory, Laurel, USA, [3]Wuhan University, School of Electronic Information, Wuhan, China, [4]GFZ Helmholtz Centre Potsdam, German Research Centre for Geosciences, Potsdam, Germany, [5]Technical University of Berlin, Institute of Geodesy, Berlin, Germany, [6]Korea Astronomy and Space Science Institute, Daejeon, Korea

The Swarm satellite mission offers unique opportunities to perform dedicated studies on equatorial night-time ionospheric F-region plasma depletions. These depletions are observed as a sharp decrease in in situ plasma density. The Swarm mission allows for the combination of these data with high-quality measurements of the magnetic and electric fields, plasma temperature, ion mass, and GPS observables that are simultaneously recorded within the constellation. This combination of data has provided insights into several characteristics of equatorial plasma density depletions, including their global occurrence distribution under different solar activity conditions, their electrodynamic features, and their severe effects on radio wave signals used for communication and navigation. However, predicting the occurrence of strong depletions remains a challenge due to their day-to-day variability, which is influenced by upward propagating atmospheric waves that play a significant role in conditioning their development.

68. Joint time-domain modelling magnetic field variations of ionospheric and magnetospheric origin. A concept and its implementation

Prof. Alexey Kuvshinov[1], Dr. Mikhail Kruglyakov

[1]ETH Zurich, Zurich, Switzerland

We present an approach to simultaneously model the spatio-temporal evolution of magnetic fields due to magnetospheric and ionospheric sources. An approach exploits two types of source parameterisation (data-based and physics-based) and accounts for 3-D electromagnetic induction effects. Using observatory data, we obtain a continuous spatio-temporal model of the external magnetic field for multiple years. We also discuss adapting the approach for analysing satellite data (like Swarm and MSS).

69. Leveraging the ESA’s Swarm overfly conditions to step into an Equatorial Plasma Bubble

Dr. Luca Spogli[1], Lucilla Alfonsi[1], Claudio Ceasaroni[1]

[1]Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy

The Swarm constellation by ESA adopted an "overfly" setup during September and October 2021, where the gap between the lower and upper satellites was the smallest since their launch. During nighttime tracks, the positioning favored to observe post-sunset equatorial plasma bubbles (EPBs). This study, recently published [1], focuses on the specific Swarm overfly from 00:41 UT to 00:59 UT on September 30, 2021, covering a highly instrumented area in South America for studying ionospheric irregularities within EPBs. Leveraging ground-based Global Navigation Satellite System (GNSS) receivers alongside Swarm plasma density measurements, we analyze the irregularities within the EPB formed around ∼60°W. The investigation delves into the various scales of these irregularities and the sequential processes along the magnetic flux tubes. We also emphasize the simultaneous occurrence of diffusion along magnetic field lines and plasma uplift, aiding in accurately interpreting the EPB's evolution and decay. The exceptional overfly conditions enable the introduction of ionosphere-related metrics, evaluated across satellite altitudes along the tracks, expanding the analysis beyond the available data along these paths. This opportunity opens avenues to estimate the impact of EPBs on GNSS signals using Low-Earth Orbit satellite data from future missions dedicated to studying the near-Earth environment and ionospheric phenomena. The overfly setup specifically allowed observations of an EPB at different altitudes, demonstrating the potential for quasi-tomographic reconstructions with larger constellations of LEO satellites orbiting at various heights. Within this context, we highlight potentially valuable metrics and their correlation with ionospheric data from ground-based GNSS measurements.

70. Enhanced Swarm-Based Climatological Models of the Non-Polar Geomagnetic Daily Variations

Dr. Arnaud Chulliat[1,2], Louis Chauvet[3], Dr. Gauthier Hulot[3], Robin Duchêne[3], Martin Fillion[1,2]

[1]University of Colorado Boulder, , United States, [2]NOAA National Centers for Environmental Information, , United States, [3]Université Paris Cité, Institut de physique du globe de Paris, CNRS, , France

Climatological models of the non-polar geomagnetic daily variations have a variety of uses, from studying ionospheric electrical current systems to correcting magnetic field survey data. Several such models were produced as part of the Dedicated Ionospheric Field Inversion (DIFI) project throughout the Swarm satellite mission. Here we present the latest version of the DIFI model, DIFI-8, inferred from ten years of Swarm Alpha and Bravo magnetic field measurements. We also present a new version of the Extended DIFI model, xDIFI-2, inferred from Swarm, CHAMP and observatory data and covering 2001-2023. Like their predecessors, these two models provide both the primary and induced magnetic fields generated by mid-latitude Sq currents and the Equatorial Electroject (EEJ) within +/- 55 degrees quasi-dipole latitudes, both at ground and at Low-Earth Orbit satellite altitudes. The new models also include the following new features that enhance their representation of non-polar geomagnetic daily variations. First, the data preprocessing incorporates corrections for toroidal magnetic fields based on a recently published climatological model (Fillion et al., 2023). Second, the so-called Wolf ratio, which relates the solar radio flux at 10.7 cm (F10.7, used as a proxy for the solar cycle) and the Sq and EEJ fields, is co-estimated with the model parameters. Third, the use of time-dependent quasi-dipole basis functions enables the capture of the slow temporal variations of the ionospheric currents associated with the secular variation of the main geomagnetic field.

71. Exploring the Swarm-Echo/e-POP Dataset: Tools for Accessing, Visualization, and Analysis

Mr. Andrew White[1], Dr. Andrew Yau[1], Andrew Howarth[1], Warren Holley[1], Troy Kachor[1], Paige Rutledge[1]

[1]University Of Calgary, Calgary, Canada

The e-POP satellite payload boasts a comprehensive array of eight scientific instruments dedicated to probing near Earth space from 325-1500km altitude. Notable among these are the Fast Auroral Imager (FAI), Magnetic Field instrument (MGF), Ion Mass Spectrometer (IRM), Electron Imager (SEI), Radio Receiver Instrument (RRI), Radio Transmitter Beacon (CERTO), and the GPS Instrument (GAP), collectively capturing measurements for study of the ionosphere, thermosphere, plasmasphere, and coupling with the magnetosphere.

Spanning 10 years of on-orbit data, this extensive data set is multifaceted, non-continuous, and large. To assist data discovery and utilization, a suite of tailored software tools has been developed, facilitating efficient access, filtering, visualization, and analysis of the data set.

72. NASA GDC Satellites as Sensors for Thermosphere Density and Drag Research

Dr. Jeff Thayer[1], Dr. Marcin Pilinski[1], Dr. Eric Sutton[1], Mr. Zach Waldron[1], Dr. Vishal Ray[2]

[1]University of Colorado, Boulder, United States, [2]Kayhan Space, Louisville, United States

The NASA GDC science team seeks to explore upper thermosphere neutral gas response to external drivers and internal processes of the ionosphere-thermosphere (IT) system. Observing the orbital behavior of the six GDC satellites offers complementary information to the GDC instrument suite. Perturbations in satellite position and velocity can be attributed to thermosphere mass density change. Consequently, with high-fidelity and high-cadence measurements of a satellite's state vector, system properties, and a full-physics satellite force model, mass density can be extracted along its orbital track using precision orbit determination (POD) methods. Furthermore, the unprecedented in-situ instrument suite allows for simultaneous, multi-property IT measurements that can be used to investigate gas-surface interactions responsible for producing drag.
This talk will outline the system requirements to enable such a capability and demonstrate a methodology by applying POD methods to satellites currently in low Earth orbit. The NASA GFSC GEODYN POD software is employed to produce precise science orbits for the ICESAT-2 spacecraft. These precise science orbits are then used to extract mass density estimates along specified orbital arcs. Simulation is also employed to address the potential errors of system requirements and how they can influence the neutral mass density estimate for GDC-like spacecraft. The extracted mass density can serve as a separate GDC data product but also used in the on-orbit validation of the GDC MOSAIC instrument.

73. Calibration of Swarm Ion Density, Drift, and Effective Mass Measurements

Dr. Johnathan Burchill[1], Dr. Levan Lomidze[1]

[1]University Of Calgary, Calgary, Canada

Using measurements from the Swarm Electric Field Instrument spherical Langmuir probes and the fixed-bias planar probe (the faceplate), the Swarm Langmuir Probe Ion Drift, Density and Effective Mass (SLIDEM) products provide estimates of effective ion mass, ion density, and the component of ionospheric ion drift parallel to the satellite velocity vector. The SLIDEM processor treats the effects of satellite-plasma interactions on the probe measurements using an eight-parameter non-linear model obtained from kinetic simulations representing corrections to the probe geometries. About 2000 coincident measurements per satellite of plasma density from SLIDEM and from the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) reprocessed dataset are used to validate the SLIDEM products. With respect to COSMIC, SLIDEM underestimates plasma density by around 10%. To improve the estimates, a simple one-parameter geometry model is calibrated which significantly reduces bias in ion density, and also brings effective mass and along-track drift into better agreement with empirical models. Spherical Langmuir probe surface area is effectively reduced by about 20% due to satellite-plasma interactions, whereas the faceplate area is unaltered. SLIDEM processing should be revised to use the simpler geometry model.

74. Revealing the EMIC wave frequency differences in the ionosphere via coordinated observations: A case study

Xin-Yan Ouyang[1], Chao Yue[2], Yong-Fu Wang[2], Jie Ren[2], Mu-Ping Yang[3], Ya-Lu Wang[1], Ying-Yan Wu[1], Xue-Min Zhang[1]

[1]Institute of Earthquake Forecasting, China Earthquake Administration, Beijing, China, [2]Institute of Space Physics and Applied Technology, Peking University, Beijing, China, [3]Liaoning Earthquake Agency, Shenyang, China

We study electromagnetic ion cyclotron (EMIC) waves based on observations from the ionosphere, magnetosphere, and ground during a geomagnetic storm recovery phase on August 28, 2018. In this case, multiple ducting EMIC waves in the ionosphere show higher frequencies in the post-midnight than those in the pre-midnight. Ionospheric EMIC wave frequency differences in magnetic local time (MLT) are consistent with MLT frequency differences in the equatorial magnetosphere, which are mainly caused by different background magnetic field at different L-shells. Moreover, we report the first observation of frequency range selections in ionospheric ducting EMIC waves and find that frequency selections depend on the magnetic field intensity in the main part of the ionospheric waveguide, with higher frequency corresponding to larger magnetic field. This study reveals the important role of background magnetic field in regulating ducting EMIC wave frequencies in the ionosphere.

75. Swarm-E Observation of Ion Composition and Small (Decameter) Scale Plasma Density Irregularities: Variability over a Solar Cycle and Impact on Magnetosphere-Ionosphere-Thermosphere (MIT) Coupling in the Topside Ionosphere

Prof. Andrew Yau[1], Ms. Victoria Foss[1], Andrew Howarth[1], Marzena Kastyak-Ibrahim[1], Andrew White[1]

[1]University Of Calgary, Calgary, Canada

The Swarm-E imaging and rapid-scanning ion mass spectrometer (IRM) combines the technique of ion time-of-flight (TOF), hemispherical electrostatic analysis, and 2D positional ion detection (imaging) to resolve the mass-per-charge (M/q), energy-per-charge (E/q), and incident direction of each detected ions, and to simultaneously measure the incident plasma current at high (1-ms) cadence. Data acquired over an 8-year period since launch (September 2013) have revealed several important new features of the plasma composition, structure, and dynamics in the topside ionosphere. These include the effects of atmospheric photoelectrons on spacecraft charging, molecular and nitrogen (N+) ion enhancements in the active-time auroral ionosphere, and decameter-scale structures in equatorial plasma bubbles, for example. We present an overview of quantitative investigations of the long- (solar-cycle time scale) and short-term (down to substorm time scale) variations of these features and associated phenomena in the context of their impact on magnetosphere-ionosphere-thermosphere coupling in the topside ionosphere.

76. How variable are Birkeland currents?

Dr. Johnathan Burchill[1]

[1]University Of Calgary, Calgary, Canada

The time-rate-of-change of high-latitude Birkeland (i.e., magnetic field-aligned) currents is estimated using the string-of-pearls formation of the Swarm satellites during late 2013. Using the space series technique, the vertical component of high-latitude electric current density (a proxy for Birkeland currents) is estimated from the along-track spatial derivative of Swarm magnetic field residuals with respect to the CHAOS-7.12 internal field model. In one case of an overflight of a visually quiescent east-west aligned auroral arc, as recorded by the Fort Yukon THEMIS camera on 1 December 2013, the current density flips from ~0.3 $\mu A/m^2$ upward to ~1.0 $\mu A/m^2$ downward in 13.7 s. Statistical maps of the total time derivative reveal median magnitude rate of change of Birkeland currents attaining 15 $nA/m^2/s$ in the northern dayside auroral zone and exceeding 30 $nA/m^2/s$ in the pre-noon sector of the southern hemisphere. Auroral Birkeland currents can change dramatically in the time it takes a satellite to cross the auroral zone. Precision control of satellite orbits is a crucial requirement for future satellite missions aiming to simultaneously resolve spatial and temporal contributions to variability in measurements of ionospheric electrodynamic and plasma parameters.

77. Beyond steady state: Solving the induction equation in the ionosphere

Dr. Karl Laundal[1], Dr Spencer Hatch[1], Dr Jone Reistad[1], Dr Heikki Vanhamäki[2]

[1]University of Bergen, Bergen, Norway, [2]University of Oulu, Oulu, Finland

The ionospheric convection electric field is usually represented as a potential field. This implies, according to Faraday's law, that the magnetic field does not change in time. Because of this, the physics of how magnetic field disturbances on ground change in time is neglected, and observed variations are instead modeled as a sequence of steady states. Here we go beyond this and model the time-varying magnetic field using Faraday's law. For a given field-aligned current pattern and given ionospheric conductivity, we calculate how the electric field and divergence-free current in the ionosphere change in time. We drive the simulation using field-aligned currents from the Swarm-based AMPS model and compare the output to results using the conventional steady-state predictions.

78. From the mantle into space: unique synergy of the Swarm and USArray for 3-D mantle induction imaging and Space Weather hazard modeling

Dr Federico Munch[1], Alexander Grayver[2]

[1]Eth Zurich, Zurich, Switzerland, [2]University of Cologne, Cologne, Germany

After 10 years in space, Swarm has delivered a unique data set and provided support for developing a new generation of models and tools throughout the community. Among other fields, this holds true for the electromagnetic induction studies. However, November 2023 not only marked the 10 years of the ESA Swarm mission in space, but also the completion of the first-of-its-kind continental wide magnetotelluric (MT) array over conterminous US, referred to as USArray.

In this contribution, we show how we synergize these two unique data sets. Specifically, we derive a new 3-D electrical conductivity model of the contiguous United States inverting more than 1500 USArray stations constrained by the global Swarm-based reference conductivity profile. The use of a novel multi-scale 3-D imaging approach based on locally refined model grids allows us to consistently incorporate a large range of spatial scales and image 3-D electrical conductivity distribution from the surface down to the mantle transition zone.

This 3-D conductivity model unravels the complex tapestry of the continent geology and tectonics and provides an unprecedented opportunity to quantify the 3-D geomagnetically induced fields taking into account realistic models of the 3-D subsurface electrical conductivity and external field variations retrieved from USArray and ESA Swarm observations.

79. How Swarm is important for improving drag modelling

Mr. Sabin Anton[1], Ms. Natalia Hładczuk[1], Dr. ir. Jose van den IJssel[1], Dr. Christian Siemes[1], Prof. dr. ir. Pieter Visser[1]

[1]Delft University Of Technology, Delft, Netherlands

The growing number of space objects within the 400 km to 600 km altitude range is generating an increased number of collision warnings, which highlights the urgent need for enhanced orbit predictions to decrease the likelihood of operational disruptions. A significant source of error in existing orbit prediction algorithms stems from the uncertainty in the drag coefficient, which also affects all thermosphere density observations derived from accelerometer and GNSS tracking data. The core of any drag coefficient calculation is the gas-surface interaction (GSI) model, which describes the momentum exchange between atmospheric particles and the satellite surfaces. Currently employed GSI models lead to drag coefficients differing up to 30%, depending on the atmospheric conditions and the selection of values for the model parameters. To reduce the uncertainty in the drag coefficient, an improved characterization GSI under conditions of free molecular flow is essential. However, the current GSI models were derived for perfectly smooth surfaces and ignore the substantial influence of surface roughness, which characterises all real surfaces. In the space environment, this effect is especially pronounced on Kapton film, which commonly exhibits roughness due to oxidation from continuous exposure to oxygen atom bombardment.

The aim of this research is to improve the aerodynamic characterisation of the Swarm satellites through a new, physics-based GSI model that incorporates the effects of the roughness of real surfaces. This model will build on the wave nature of gas molecules and leverage electromagnetic wave scattering theory for a physics-informed expression of the scattering kernel. The resulting three-parameter GSI model will be calibrated using the accelerations derived from the GNSS tracking data of the Swarm satellites. Two of the three parameters will be selected based on molecular dynamics simulations for representative smooth surfaces, leaving the surface roughness parameter as the sole variable to be estimated from Swarm data. The drag coefficient is very sensitive to the GSI model when the satellite orientation with respect to the atmospheric flow changes. Therefore, any error in the GSI model can be revealed by comparing the density observations from two satellites flying in close proximity in substantially different orientations. Thus, attitude manoeuvres of formation flying satellites, such as the manoeuvre performed by the Swarm A and C satellites in May 2014 for the magnetometer characterisation, offer perfect opportunities to improve GSI models and, consequently, drag modelling.

80. Determination of field-aligned currents using the dual-spacecraft approach in the Swarm constellation mission

Dr. Guram Kervalishvili[1], Jan Rauberg[1], Prof Hermann Lühr[1], Dr Monika Korte[1]

[1]GFZ German Research Centre for Geosciences, Potsdam, Germany

Field-aligned currents (FACs) play a crucial role in the ionosphere-magnetosphere coupling in near-Earth space, and accurate estimates are essential to understand their distribution. The European Space Agency's (ESA) Swarm mission consisting of the three identical satellites Alpha, Bravo, and Charlie (A, B, and C) plays an important role here. The mission was launched on 22 November 2013 into a near-polar orbit and the initial constellation was achieved on 17 April 2014, with Swarm A and C flying side-by-side at an altitude of about 470 km and Swarm B at an altitude of around 520 km. The lower pair of Swarm satellites, with 1.4° longitudinal separation at the equator, an along-track separation between 4 and 11 seconds, and the crossing point of orbits above ±87°, is very well suited for determining Dual FACs based on high-precision multi-satellite magnetic field measurements. Time series of field-aligned and radial current densities along the satellite orbit based on the dual-satellite method are available as a regular Swarm data product (https://swarmhandbook.earth.esa.int/catalogue/SW_FAC_TMS_2F).

The Swarm operational processor automatically generates these FAC products based on the prototype algorithm developed by the GFZ team. This algorithm was developed for the initial configuration of Swarm A and C satellites, which was not changed until October 2019. This means that the configuration of the Swarm A and C satellites is a critical factor for the algorithm to produce valid results. However, the initial constellation configuration was disrupted due to several orbit changes that occurred between October 2019 and August 2023. As a result, the production of the dual FAC product was halted during the affected periods and required manual intervention. An update of the processing algorithm, accounting more flexibly for variations in the constellation configuration, is required to ensure the accurate functionality of the automatic operational processor during past and potential future manoeuvres. Here, we present and discuss results for the dual FAC data based on an adapted prototype processor. The updated algorithm, which considers differences in equatorial separation and position of the crossing point, is capable of utilizing the dual-satellite approach to generate FAC data from a range of constellation configurations, in particular including the time from 2019 to 2023. Note that the dual FACs cannot be reasonably determined during periods when the along-track separation between Swarm A and C satellites exceeds 11 seconds (October 2021 – January 2022, May – July 2022, April – June 2023). Overall, the updated algorithm provides unique new dual FAC data with great opportunities for scientific investigations.

81. Physics-informed Neural Networks for the Improvement of Platform Magnetometer Measurements

Mr. Kevin Styp-Rekowski[1], Ingo Michaelis[2], Dr. Monika Korte[2], Prof. Claudia Stolle[3]

[1]TU Berlin + GFZ Potsdam, Berlin, Germany, [2]GFZ Potsdam, Potsdam, Germany, [3]IAP Kühlungsborn, Kühlungsborn, Germany

Space-based measurements of the Earth's magnetic field with a suitable spatiotemporal coverage help to understand our geomagnetic and space environment. High-precision magnetic field satellite missions have unrevealed geomagnetic research, e.g., enable frequently updated high-precision geomagnetic field models and ionospheric investigations during geomagnetically disturbed as well as quiet times. However, these missions currently come with limited spatial coverage. But, many satellites carry platform magnetometers for orbit control. After an appropriate recalibration to reduce initial noise, they are suitable for geospace research in combination with high-precision missions.
We introduce an expansion of our earlier machine learning methodology to be applied as an automatic post-launch calibration of platform magnetometers. Our contribution involves a new physics-informed layer based on the Biot-Savart formula for dipoles to efficiently correct disturbances caused by electric current-induced magnetic fields. In addition, the B-field estimates of the AMPS model are combined with the B-field estimates of the CHAOS-7 model, improving the reference model for the calibration, especially for the polar regions. We have applied this new methodology for two satellite missions, GOCE and GRACE-FO, achieving mean residuals of about 7nT and 4nT for low- and mid-latitudes, respectively. The datasets have been published and are freely available.

82. A model to estimate the L-band amplitude scintillation index from Swarm faceplate electron density measurements

Dr. Rayan Imam[1], Luca Spogli[1,2], Lucilla Alfonsi[1], Claudio Cesaroni[1], Yaqi Jin[3], Lasse B. N. Clausen[3], Alan Wood[4], Yuhao Zheng[5], Chao Xiong[5,6], Wojciech J. Miloch[3]

[1]Istituto Nazionale Di Geofisica E Vulcanologia, Italy, [2]SpacEarth Technology, Italy, [3]University of Oslo, Norway, [4]University of Birmingham, UK, [5]Wuhan University, China, [6]Hubei Luojia Laboratory, China

Swarm 16 Hz faceplate (FP) electron density measurements sample the plasma density with sub-kilometre spatial resolution. We leverage this capability to develop a Swarm amplitude scintillation index (S4) for measuring irregularities that affect L-band Global Navigation Satellite Systems (GNSS) signals. Such an index from Swarm measurements is important for filling measurement gaps at locations where ground-based GNSS scintillation monitoring receivers are not available, for example, over the oceans.

The model relies on Rino's formula for weak scattering, which models the ionosphere as a thin layer at the height of the peak electron density (hmF2). However, Swarm flies slightly higher than hmF2. We rely on models to reconstruct the electron density profile and translate Swarm measurements to their equivalent values at hmF2. We show the model's details and present results of the estimated Swarm S4 values using Swarm's 10 years of electric field instrument (EFI) FP data.

To validate Swarm S4 model, we rely on S4 measured by GNSS scintillation monitoring receivers on the ground. We find conjunctions between Swarm passes and the signals received by over 20 scintillation monitoring receivers. We show the statistical error in estimating S4. We sort the analysis according to the space weather conditions and the geomagnetic coordinates.

Furthermore, we validate the electron density profile utilized by the Swarm S4 model against values measured by co-located GNSS and ionosondes. In particular, we investigate the parameters that affect the accuracy of Swarm S4 the most. We draw conclusions about the model inputs' accuracy needed for bounding Swarm S4 to certain error constraints.

Finally, we comment on the outer scale wavenumber, a crucial parameter for calculating S4 and we present the optimization of this parameter to obtain the least error in estimating Swarm S4.

With the 16 Hz EFI FP measurements being made available more frequently in the last few years, and with Swarm's introduction of the FAST products, this S4 data product has the potential to be used for space weather applications and for near real-time specification of the ionosphere.

83. Space Weather Monitoring by Swarm Magnetic Field Observations: The SFAC Index

Dr. Adrian Blagau[1], Dr. Octav Marghitu[1], Dr. Vlad Constantinescu[1], Dr. Malcolm Dunlop[2], Dr. Guram Kervalishvili[3], Dr. Matthew Friel[4]

[1]Institute for Space Science, Bucharest-Magurele, Romania, [2]Rutherford Appleton Laboratory Space, Science and Technology Facilities Council, Harwell Campus, Oxfordshire, United Kingdom, [3]German Research Centre for Geosciences, Potsdam, Germany, [4]Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, United States

By providing high-precision magnetic field measurements at suitable altitude, the Swarm mission offers a unique opportunity to simultaneously monitor the field-aligned current (FAC) system (by in-situ measurements) and the polar electrojet current (PEJ) in the ionosphere (by remote observations). In addition, Swarm provides numerous conjunctions with ground-based observatories (GBOs), where the variations in the horizontal component of the recorded magnetic field, dH/dt, driven mainly by PEJ variations, can be used as a proxy for the geomagnetic induced currents (GICs) and related space weather (SWE) effects.
These circumstances support the design and validation of the Sheet FAC (SFAC) index, proposed under the (Swarm-DISC) SWESMAG project, to help the characterization of the 3D ionospheric current system and for monitoring the risk of intense and potentially harmful GICs on the ground. The SFAC quantifies the large-scale FAC system through the maximum absolute value of the magnetic perturbation for each Swarm crossing of the auroral oval and can be easily provided as a near real-time index at a cadence defined by the Swarm orbital period.
The SFAC relevance in the SWE context has been proved by correlation studies with other integral quantities that characterize the ionospheric electrojet current, such as the Auroral Electrojet index, based on ground data, and (even better) the Polar Electrojet index, based on Swarm data. Similarly, the SFAC appears to correlate well also with the horizontal magnetic field perturbation at specific GBOs, near the Swarm magnetic footpoint. Based on the SWESMAG project results, we plan to extend the same approach to other low Earth orbit satellites, with the potential to greatly increase the data available for SWE monitoring and the accuracy of the predicted geomagnetic conditions.

84. Ionosphere currents react to the solar eclipse on 21 June 2020

Ms. Fengjue Wang[1], Prof. Chao Xiong[1], Mr. Yuyang Huang[1]

[1]Wuhan University, Wuhan, China

The solar eclipse has a great influence on the variability of the ionosphere because of the obscuration of solar radiation. In addition to the electron density reduction, the ionospheric currents show also prominent variations during solar eclipse. In this study we focused on the solar eclipse happened on 21 June 2020, and the magnetic field measurements from Swarm satellites as well as ground-based stations are used. Taking seven stations at a fixed longitude, the latitudinal profile of magnetic field variations has been used to reveal the ionospheric current profiles, and the simultaneous measurements from Swarm satellites agree well with signals detected from ground-based stations. With the continuous measurements by the chain of ground stations, how the intensity and configuration of ionosphere currents develop during the solar eclipse are investigated.

85. Rescaling of magnetic signals due to ocean circulation by assimilating Swarm satellite observations

M.sc. Aaron Hornschild[1], Dr. Jan Saynisch-Wagner[1], Dr. Julien Baerenzung[1], Prof. Dr. Maik Thomas[1]

[1]GFZ German Research Center For Geosciences, Potsdam, Germany

The movement of conductive seawater through Earth's magnetic field due to the global ocean circulation induced large-scale secondary electromagnetic signals.
Since these magnetic signals are in principle detectable by geomagnetic satellite observations like the current Swarm mission, they provide an interesting source of information about the ocean circulation.
However, contrary to magnetic signals induced by tides, the signals resulting from ocean circulation have not been identified yet.
We demonstrate an approach for this identification, where the crucial separation from other magnetic contributions is achieved by predefining the temporal behavior of the oceanic component using presumed estimates. This approach was tested in an observing system simulation experiment and applied to real Swarm magnetometer observations. Various a priori assumed ocean circulation-induced magnetic fields are rescaled by the assimilation of Swarm magnetometer data.
We present the resulting scale factors and evaluated the outcomes in terms of identifying magnetic signals caused by ocean circulation.

86. Improving our understanding of the ionosphere by using Swarm mission as a constellation

Prof. Dr. Chao Xiong[1], Prof. Hermann Lühr[2], PhD student Fengjue Wang[1], Prof. Claudia Stolle[3], PhD student Chunyu Xu[1], PhD student Simin Wang[1], Associated Prof. Yunliang Zhou[1], Prof. Jaeheung Park[4], Associated prof. Fan Yin[1], Dr. Guram Kervalishvili[2]

[1]Wuhan University, Wuhan, China, [2]GFZ German Research Centre for Geosciences, Potsdam, Germany, [3]Leibniz Institute of Atmospheric Physics at the University of Rostock, Kühlungsborn, Germany, [4]Korea Astronomy and Space Science Institute, Daejeon, South Korea

ESA' Swarm mission, consisting of three satellites, provides unique opportunities to improve our understanding of the ionospheric structures that cannot be achieved by single-satellite missions. In this study, we provide an overview of our recent work focusing on the ionospheric structures, based on observations of Swarm from the constellation perspective. Our main results can be summarized as:

1) the initial mission phase, when three satellites fly in a configuration as a string of pearls, is very useful to investigate the small-scale structures of ionospheric irregularities as well as the small-scale field-aligned currents (FACs) at auroral latitudes.

2) The lower-pair flying Swarm A and C, with a longitudinal separation of 1.4°, can well reflect the longitudinal (or local time) gradient of large-scale ionospheric structures, e.g., the equatorial ionization anomaly (EIA) and equatorial electrojet (EEJ). The improved FACs calculated with Swarm dual-satellite reveal that the conventionally used FACs calculated with single-satellite approach underestimate the FACs' intensity at auroral and middle latitudes; in addition, the radial current from single-satellite approach is contaminated by EEJ at American sectors due to large magnetic declination in this region.

3) the counter-rotation period between Swarm A/C and B, provides also good opportunity to investigate the field-aligned scale length of post-sunset equatorial plasma bubbles, as well as the propagation of upstream waves at ionospheric altitude.

87. 100 000 whistlers detected during ASM burst mode campaigns: uncovering seasonal and solar cycle dependencies

Dr. Pierdavide Coïsson[1], Dr. Gauthier Hulot[1], Mr. Martin Jenner[1], Mr. Louis Chauvet[1], Mr. Robin Deborde[1], Prof. Janusz Mlynarczyk[2], Mr. Jerzy Kubisz[3]

[1]Université Paris Cité, Institut de physique du globe de Paris, CNRS, Paris, France, [2]AGH Universit, Krakow, Poland, [3]Jagiellonian University, Astronomical Observatory, Krakow, Poland

Since 2019, the Absolute Scalar Magnetometers of Swarm Alpha and Bravo acquired every month one week of data in burst-mode. The Local Time of the Ascending Node of these satellites drift by about one hour every ten days, therefore each campaign covered a specific temporal sector. Over the years, a complete coverage of all local times has been achieved. Recently, this coverage has been extended to all local times for each season. The acquisition campaigns started during the minimum of the solar cycle, and keep being acquired during the current solar maximum. When the Swarm satellites were in close counter-rotating orbits, several overlapping acquisition campaigns were also conducted in 2021 and 2022.
We process these data to detect and characterise whistler signals in the Extremely Low Frequencies (ELF). Whistler data are now distributed as level 2 scientific product of the mission. The corresponding files include their dispersion, their intensity and the estimated time when these signals entered the ionosphere. It is expected that by the time of this presentation the dataset will exceed 100 000 whistlers events.
Global statistics of whistler occurrences reveal their geographical, local-time, seasonal and solar activity dependencies. These correlate with the lightning activity in the troposphere, with powerful strikes being able to generate whistlers detected several thousands of km away, since ELF signals can propagate at very far distance in the waveguide between the ground the lower ionosphere. We used data from the World Wide Lightning Location Network (WWLLN) and the World ELF Radiolocation Array (WERA) to identify the strikes that originated remarkable whistlers.
We present several remarkable whistler events and discuss the propagation properties of these signals.

88. Reconstructing the ionospheric and magnetospheric magnetic fields using observatory and satellite observations

Mr. Jingtao Min[1], Dr. Alexander Grayver[2]

[1]ETH Zurich, Zurich, Switzerland, [2]University of Cologne, Cologne, Germany

Time-varying electromagnetic field observed on the ground or at a spacecraft consists of contributions from multiple external electric source currents, including the ionospheric currents and the magnetospheric currents. The spatio-temporal structure of the ionospheric and magnetospheric magnetic fields is not only of interest for studying these two current systems, but is also essential in space weather hazard evaluation, and electromagnetic induction studies. While conventional Gauss representation based on ground observatory data cannot distinguish between ionospheric field and magnetospheric field, the addition of satellite dataset makes it possible. The ionospheric field, which appears as the external contribution to ground observatories, changes its status to internal contribution when viewed from satellites. This geometric arrangement makes it possible for the ionospheric signal to be separated from the magnetospheric counterpart. In this study, we present simultaneous reconstruction of both the ionospheric and magnetospheric magnetic field, utilising both ground observatory and satellite data. Preliminary results show that the two external sources can be individually characterised in geomagnetic modelling without strong prior assumptions on the frequency band or geometry of either sources.

89. Magnetic eigenmodes in the plesio-geostrophic model

Mr. Jingtao Min[1], Prof. Andrew Jackson[1], Dr. Stefano Maffei[1]

[1]ETH Zurich, Zurich, Switzerland

Temporal variations of the geomagnetic field at and above the Earth's surface contain contributions from multiple electric current systems, the most dominant of which is the electric current generated by the fluid flow in the electrically conductive outer core. Knowledge of the outer core dynamics is crucial in understanding the evolution of the geomagnetic field. In the Earth's outer core, rapid rotation of the Earth places the fluid near the geostrophic force balance, organising the flow into columnar structures. Making use of the columnar flow ansatz, the recent plesio-geostrophic (PG) model shows that by taking axial integrals that are symmetric or antisymmetric with respect to the equatorial plane, the ideal magnetohydrodynamic equations in 3-D space can be described by a set of quantities on 2-D manifolds, allowing more efficient computation, with parameters in the parameter space that are closer to the real Earth. In this study, we compute the magnetic eigenmodes using the PG equations, linearized around certain background fields. This demonstrates the capability and tests the validity of the PG model. The eigenmode calculation is the first of several steps towards a geomagnetic data assimilation framework that utilises the PG model as the dynamical core, which would hopefully provide better estimates of the physical parameters and dynamics of the deep interior.

90. Identification of STEVE-SAID Events in Swarm Data

Mr. Harshit Panwar[1], Gareth Perry[1], Andrew Gyakobo[1], Lindsay Goodwin[1], William Archer[2]

[1]New Jersey Institute Of Technology, Newark, United States , [2]Canadian Space Agency, ,

The optical phenomenon known as Strong Thermal Emission Velocity Enhancement (STEVE) is associated with an intense Subauroral Ion Drift (SAID). This subset of events occurs under the following conditions based on in situ measurements: high plasma velocities, high electron temperatures, and low plasma densities, all of which are latitudinally narrow in extent and occur in the sub-auroral region. This research aims to provide an algorithmic approach to characterize the occurrence of coupled STEVE and SAID to identify such events efficiently with in situ measurements. We present the current iteration of the algorithm which is a peak-finding routine for electron temperature spike identification combined with a cross-correlation metric against plasma density drops. This is followed by a plasma density drop-detection routine to separate true drops from transits of the plasma trough. We observe ambiguity in discerning the characteristics between the two classes of drops, suggesting the need for a more defined criteria to classify the density signatures. Future work will involve conducting a statistical analysis to investigate the probability of temperature spikes relative to their geomagnetic location.

91. Retrieval of tidal magnetic signals from satellite data: recent progress and the road ahead

PD Dr. Alexander Grayver[1], Christopher Finlay[2], Nils Olsen[2]

[1]University Of Cologne, Cologne, Germany, [2]DTU Space, Copenhagen, Denmark

Magnetic signals induced by the oceanic tidal flow can now be globally mapped using the ESA Swarm data. They are used to study the electrical conductivity of the oceanic upper mantle and are potentially seen as proxy signals for remote sensing of Essential Climate Variables such as the Ocean Heat Content (OHC). Here, we present the most recent results of retrieving the tidal magnetic signals due to four tidal constituents from diurnal and semi-diurnal bands (M2, N2, O1, Q1). To this end, we used more than 9 years of magnetic field measurements from the ESA Swarm trio together with a newly developed data selection approach and modelling tools. By utilizing longer time series and by including field gradients, which help filter out small scale noise, we achieved much improved S/N ratio and higher spatial resolution of retrieved signals compared to the previous generation of models. Additionally, we report the uncertainty of resulting models and present a systematic comparison of the herein retrieved oceanic tidal magnetic signals against all other published models.

92. New electrical conductivity profile of the mantle constrained by the joint inversion of oceanic and magnetospheric magnetic signals observed by ESA Swarm

PD Dr. Alexander Grayver[1], Laura Cobden[2], Federico Munch[3], Nils Olsen[4]

[1]University Of Cologne, Cologne, Germany, [2]Utrecht University, Utrecht, Netherlands, [3]ETH Zurich, Zurich, Switzerland, [4]DTU Space, Copenhagen, Denmark

Satellite-detected magnetic signals of magnetospheric and oceanic origins carry information on the electrical conductivity of the Earth's mantle. Due to different period bands, these signals can be used to probe distinct regions of the mantle. While tidal magnetic signals are sensitive to conductivity distribution in the upper mantle, primarily the lithosphere and asthenosphere, magnetospheric signals lack resolution there, but can constrain regions across the transition zone and, thanks to the sufficiently long mission time, even the lower mantle structure. This prompts simultaneous inversion of both signals to get improved resolution across the whole depth column. In this contribution, we derive a new reference conductivity profile of the mantle from the crust down to the mid lower mantle using the latest ESA Swarm oceanic and magnetospheric signal products and interpret the obtained conductivity jointly with a seismic tomography model in terms of the mantle mineralogy, temperature and the water content constrained by thermodynamic phase equilibria simulations.

93. Swarm for Ocean Dynamics

Prof. Chris Finlay[1], Jakub Velímský[2], Clemens Kloss[1]

[1]DTU Space, Lyngby, Denmark, [2]Charles University, Prague, Czech Republic

Satellite magnetic field observations have the potential to provide much needed information on changes in ocean dynamics and heat content that are key components in the Earth system. It is well established that the oceans produce a time-varying magnetic field by motional induction and that its amplitude is measurable at satellite altitude. However it remains a major challenge to efficiently extract the small signal of ocean variability from the magnetic measurements made by the Swarm mission.

In the Swarm for Ocean dynamics project, over the next 18 months, we will work towards retrieving the observed Ocean-Induced Magnetic Field (OIMF) by (i) implementing a dedicated scheme for processing Swarm magnetic field data with a focus on the time-varying internal signals and including appropriate corrections for known magnetospheric and ionospheric signals, (ii) high resolution global modelling of the time-dependent internal field at Earth's surface based on this processed dataset, and (iii) applying algorithms to extract the time-varying OIMF signal from the resulting field model based on the OIMF's expected patterns of spatio-temporal variability. The latter algorithms will be guided by the best available forward models of the ocean magnetic signal based on the latest oceanographic information and advanced numerical modelling. The forward models will also be used for synthetic tests of our scheme for retrieving the OIMF. In this contribution we will discuss plans this project and results of some initial investigations.

94. Core field evolution from a decade of observations by the Swarm satellites

Prof. Chris Finlay[1], Clemens Kloss[1], Mikkel Otzen[1]

[1]DTU Space, Lyngby, Denmark

We present a model describing the evolution of Earth's magnetic field at the core-mantle boundary, based on ten years of magnetic field measurements made by the Swarm satellite trio. The availability of consistent, high quality, data from a satellite constellation spanning more than a decade has opened new possibilities for field modelling and is now providing fresh insights into core processes and the geodynamo. We make use of a maximum entropy modelling technique that helps to separate internal field contributions from the core and the lithosphere and results in a stable, high resolution, image of the core-mantle boundary field.

The radial field at the core-mantle boundary, its rate of change (secular variation) and its acceleration as seen by the Swarm satellites will be presented. Prominent changes in the core field over the past decade include the westward motions of pairs of low latitude flux concentrations, changes in normal flux bundles and reversed flux patches in the polar region, and the gradual evolution of reversed flux patches related to the South Atlantic weak field anomaly. Implications regarding our understanding of the geodynamo and future opportunities, in particular related to complementary observations expected from the MSS-1 and NanoMagSat missions, will be discussed.

95. High-precision magnetometry from LEO satellites, from Swarm to the next generation NanoMagSat mission, lessons learnt and latest progress

Dr. Gauthier Hulot[1], Dr Jean-Michel Léger[2], Dr Pierdavide Coïsson[1], Mr Thomas Jager[2], Mr Louis Chauvet[1], Mr Florian Deconinck[3]

[1]Université Paris Cité, Institut de Physique du Globe de Paris, CNRS, Paris, France, [2]CEA-Leti, Université Grenoble Alpes, MINATEC, Grenoble, France, [3]Open Cosmos Ltd., Didcot, United Kingdom

ESA Swarm satellites carry a magnetometry payload consisting of a relative flux gate vector magnetometer (VFM), a set of star trackers (STR), and an absolute scalar magnetometer (ASM) developed by CEA-Léti and provided by CNES as a costumer furnished instrument. The primary role of the ASM is to provide precise 1 Hz absolute field intensity measurements, while the VFM and STR provide the additional data needed to accurately reconstruct the vector field. This magnetometry payload has provided a remarkable set of nominal vector data, which was extensively used for multiple investigations, as illustrated by the many results presented in this Swarm celebration. Each ASM instrument, however, can also produce its own self-calibrated 1 Hz experimental vector data, or, when requested, 250 Hz scalar burst mode. Self-calibrated 1 Hz experimental vector data have routinely been produced ever since launch, and substantial amount of scalar burst mode sessions have now also been run, mostly since 2019, when the decision was made to run such sessions one week per month on both the Alpha and Bravo satellites. In this presentation, we will illustrate the added value both these datasets brought to the Swarm mission, with the self-calibrated 1 Hz experimental vector data contributing to improvement and validation of the nominal dataset, and the burst mode data bringing new science opportunities. We will next discuss the lessons learnt from operating the ASM instruments on Swarm and how these led to the development of new miniaturized magnetometers, providing even better performance and offering further science capabilities. As these magnetometers will be key elements of the payload to be deployed on the three nanosatellites of the NanoMagSat constellation, we will finally also report on the latest technical and programmatic status of the NanoMagSat project, which aims at complementing and enhancing the science return of the Swarm mission. NanomagSat is being developed in the context of the ESA Scout program and the decision for its implementation is now anticipated to be tabled for the ESA PBEO in February 2024.

96. Sensitivity of Swarm satellite data to the electrical conductivity of the lower mantle

Dr. Jakub Velímský[1]

[1]Charles University, Praha 8, Czech Republic

Whereas the surface of the Earth is directly observable, relatively little is known about the topography and thermochemical structure of the CMB and its connection to the Large Low Seismic-Velocity Provinces (LLSVPs) and Ultra Low Velocity Zones (ULVZs). While a thin, electrically highly-conductive layer above the CMB is admissible by long-period electromagnetic studies, its thickness, lateral extent and thermochemical structure, or its connection with the seismologically-determined ULVZs remain unconstrained.
Velímský and Knopp (2021) have used recent Swarm-based Level-2 products (denoted MMA) describing the time-varying magnetospheric field, and its induced counterpart, to obtain a low-resolution 3D electrical conductivity distribution in the Earth's mantle. By Hessian analysis, they demonstrated that the data sensitivity is focused to the region of the upper lower mantle (ULM), spanning the depth range from the bottom of the transition zone (670 km) down to 1300 km. The principal limitation of their approach is the limited spatial resolution of the induced field, which is obtained from along-track observations using the Comprehensive Inversion (Sabaka et al., 2013, 2018). Martinec and Velímský (2022) developed a new method for the extraction of the induced part from Swarm magnetic data for large magnetic storms, introducing improved treatment of the polar electrojets and field-aligned currents (further denoted as MMC model). They showed that the induced part can be found up to degrees 5 to 7, while the inducing (external) part extracted from Swarm data contains statistically significant spherical harmonics up to degree two, at most. A richer spectrum of the induced magnetic field in Swarm data will allow us to study the sensitivity of induced magnetic field on a 3D electrical distribution in the ULM region.

The sensitivity analysis uses the forward and inverse solver for electromagnetic induction in a 3D Earth (Velímský and Martinec, 2005; Velímský 2013). The solver runs computations in time domain which is consistent with a transient time behaviour of Swarm magnetic field during large magnetic storms. We use the existing 1-D and 3-D conductivity models derived from MMA to establish the sensitivity of MMC to conductivity variations from the bottom of the transition down to the CMB. A misfit between the internal part of MMC, and the prediction of the numerical simulations is complemented by calculations of its first and second derivatives with respect to conductivity parameters, using the adjoint method (Maksimov and Velímský, 2017).

97. A Machine Learning Model of High-Latitude Plasma Convection

Dr. Levan Lomidze[1], Dr. Johnathan K. Burchill[1], Dr. David J. Knudsen[1]

[1]University of Calgary, Calgary, Canada

The high-latitude ionosphere is subject to an electric field of magnetospheric origin that plays one of the key roles in ionospheric plasma dynamics and energetics. Its study is additionally important for better understanding of the physical processes in the coupled solar wind-magnetosphere system. To date, several ground- and satellite-based observations have been used to obtain information about these electric fields, or equivalently on the corresponding plasma E×B drift and electric potential. Their data were also utilized to develop empirical models of ion convection, which represent critical inputs for physics-based global ionosphere models. Even though the amount of data used in recent models has increased noticeably, the approach to constructing them remains largely unchanged and is based on orthogonal functions and statistical regression techniques with a priori specified terms in the regression model. This, in turn, can result in bias introduction in the form of potential variation and omission of important model input variables (because of unknown functional form). In this work we employ nearly ten years of electric field data from Swarm satellites' Thermal Ion Imagers (TIIs) and use artificial neural networks (ANNs) to develop a model of the plasma convection for both northern and southern high-latitude ionosphere. Different from other empirical models of the electric field, the new Swarm TII-ANN convection model explicitly accounts for the variation by day of year, universal time, solar and geomagnetic activity, and 3-D interplanetary magnetic field and solar wind velocity. We first present the main steps undertaken to develop and test the model. Next, we examine the high-latitude potential distribution from Swarm TII-ANN under a variety of solar and geophysical conditions, and then compare results with other models and independent measurements.

98. A decade-long record of temporal gravity observed by the Swarm satellites

Dr. Joao Encarnacao[1], Daniel Arnold[2], Ales Bezdek[3], Christoph Dahle[4], Junyi Guo[5], Jose van den IJssel[1], Adrian Jaeggi[2], Jaroslav Klokocnik[3], Sandro Krauss[6], Torsten Mayer-Guerr[6], Ulrich Meyer[2], Josef Sebera[3], CK Shum[5], Pieter Visser[1], Yu Zhang[5]

[1]Delft University of Technology, Delft, Netherlands, [2]Astronomical Institute of the University of Bern, Bern, Switzerland, [3]Astronomical Institute of the Czech Academy of Sciences, Prague, Czech Republic, [4]GFZ German Research Centre for Geosciences, Potsdam, Germany, [5]School of Earth Science of the Ohio State University, Columbus, Ohio, USA, [6]Institute of Geodesy of the Graz University of Technology, Graz, Austria

While studying the Earth's magnetic field has been the primary scientific objective, the Swarm satellites also collect GPS data with sufficient accuracy to enable quantifying monthly changes in the global gravity field at a spatial resolution longer than 1,500 km (half-wavelength). These monthly models, available from 2014 to the present, are independent of other gravimetric data sources or any a priori information, and do not assume any temporal and spatial correlations. This time series now also provides global time-variable gravity field information for the period between GRACE and GRACE-FO and for short breaks in their data records. Given the robust condition of the Swarm satellites, there is a likelihood that they will continue to provide gravimetric information during any potential gap in the GRACE-FO data, and possibly beyond.

The team is composed of The Astronomical Institute of the University of Bern, the Astronomical Institute of the Czech Academy of Sciences, the Delft University of Technology, the Institute of Geodesy of the Graz University of Technology, and the School of Earth Sciences of the Ohio State University, who produce individual gravity field models, each of which exploits different and independent gravity field inversion strategies. The individual solutions are combined at the solution level using weights derived with Variance Component Estimation, by the International Combination Service for Time-variable Gravity Fields (COST-G), to ensure the published models are largely unbiased. We publish the models every 3 months at ESA’s Swarm Data Access server (https://swarm-diss.eo.esa.int) as well at the International Centre for Global Earth Models (http://icgem.gfz-potsdam.de/series/02_COST-G/Swarm), with the support of the European Space Agency and the Swarm Data, Innovation, and Science Cluster.

We demonstrate the geophysical signal captured by Swarm's GPS receivers across large regions including hydrological and cryospheric basins. We also examine the errors represented by the variability of the signal represented by the Swarm models over the oceans and their agreement with GRACE and GRACE-FO datasets. Our analyses cover the gaps in GRACE/GRACE-FO data, highlighting the significance of Swarm in mitigating the absence of low-low satellite-to-satellite tracking data during past and future gap periods.

99. Characterizing magnetospheric signals in the geomagnetic observations.

Phd. Student Yalei Shi[1], Vincent Lesur, Erwan Thebault

[1]Institut De Physique Du Globe De Paris, Paris Cedex 05, France, [2]Laboratoire Magma et Volcans - University Clermont Auvergne, Clermont Ferrand, France

The geomagnetic field, as observed at the Earth's surface or satellite altitudes, is the combination of signals generated by several sources: internal sources due to the liquid outer core flow and magnetized rocks in the lithosphere, and external sources due to electric currents in the ionosphere and magnetosphere. We describe an approach for modeling the magnetospheric contribution to the geomagnetic field, based on magnetic observatory data. Magnetic survey satellite data provide a good spatial resolution for fields generated in the Earth, but their spatiotemporal resolution is limited for rapidly varying external magnetic fields. Modern magnetic observatories, located over a large range of latitudes and longitudes, record minute-mean (or second-mean) vector magnetic data. Therefore, magnetic observatories provide together a data set with a better temporal resolution particularly well suited to characterizing magnetospheric signals. The objective of this work is to produce a reliable description of the observed magnetospheric components up to spherical harmonic degree 6 with a time resolution of an hour or better. The approach followed is based on a Kalman filter and correlation-based modeling. In order to properly separate fields of internal and external origins in magnetic observatory data, the data are firstly treated by removing the core contribution as described by MCM core model, and then selected for night time (from 23:00 to 05:00 UT) and geomagnetically quiet time (Dst between -30 nT and 30 nT). The first results are presented and compared with an approach where the day-side data are used and the magnetospheric model co-estimated with the ionospheric field contribution in the observatory components. We anticipate that using day-side data is a necessary step to derive robust magnetospheric field models.

100. Ten Years of Ionospheric Electrodynamics with Swarm - From Events to Statistics to Models

Prof. David Knudsen[1], Dr. Johnathan Burchill[1], Dr. Alexei Kouznetsov[1], Dr. Levan Lomidze[1]

[1]University Of Calgary, Calgary, Canada

Considered separately, magnetic and electric field measurements provide information on ionospheric currents and flows. Combined, they represent electrodynamic processes that include energy transfer, ionospheric conductance, and wave behavior. While these electrodynamic parameters have been measured in-situ for decades, Swarm has brought significant advances through the precision and stability of its measurements, orbital coverage, multi-point capability, and now, its decade-plus database of observations – significantly longer than any previous mission of its kind. Ultimately, the scientific legacy of this unprecedented dataset will be preserved in future ionospheric models, both assimilative and, eventually, physics-based. This talk will survey scientific discoveries made possible by Swarm electric field measurements in particular, beginning with event studies early in the mission, then statistical results made possible by the large and growing dataset, and finally, assimilative models currently under development.

101. Lunar tide in the equatorial electrojet

Dr. Yosuke Yamazaki[1], Claudia Stolle[1], Patrick Alken[2]

[1]Leibniz Institute Of Atmospheric Physics, Kühlungsborn, Germany, [2]University of Colorado, Boulder, USA

The equatorial electrojet is a narrow ribbon of ionospheric current flowing along the dayside magnetic equator at an altitude of 106 km. It is known that the equatorial electrojet depends not only on solar time but also on lunar time, due to the effect of the atmospheric lunar tide. Studying lunar tidal effects on the ionosphere provides useful information for whole atmospheric models to evaluate the ionospheric response to the well-known lunar tidal forcing. Yamazaki et al. (2017) examined characteristics of the lunar tidal variation in the equatorial electrojet using 10 years of CHAMP satellite observations (2000-2010) and 3 years of Swarm satellite data (2014-2016). We revisit the subject with 7 more years of Swarm observations (2017-2023).

102. Swarm satellites 10 years in orbit - status and forecast

Mr. Thomas Usbeck[1]

[1]Airbus Defence and Space, Friedrichshafen, Germany

The three SWARM satellites are successfully operating in orbit since 10 years. This presentation gives an overview of the status of the three satellites and it's main platform subsystems Data Handling (OBC H/W and S/W), Communication, Power, Thermal, AOCS and Propulsion after 10 years in orbit. The few main platform issues and how they were solved are briefly described. The status of the life limited items, i.e. thruster cycles, propellant mass and battery capacity fade, is presented as well as a forecast wrt. the achievable lifetime of the SWARM satellites. Further the status of the ground testbeds maintained at Airbus premises to support in-orbit S/W maintenance is given. Finally an outlook of potential enhancements for a future SWARM platform, based on the improvements of the GRACE-C wrt. the GRACE-FO platform, is presented.

103. Detecting the Auroral Oval through Swarm ionospheric magnetic field measurements and CSES-01 electric field observations.

Dr. Emanuele Papini[1], Dr. Mirko Piersanti, Dr. Enkelejda Qamili, Dr. Giuseppe Consolini, Dr. Giulia D'Angelo, Mr. Dario Recchiuti, Dr. Piero Diego

[1]INAF, Roma, Italy

We present the results of a study of the electromagnetic field properties in the Auroral Oval (AO) region. We exploit magnetic field measurements taken by the VFM instruments onboard Swarm B and electric field observations by the EFD instrument onboard the CSES-01 spacecraft. Both satellites are Low-Earth orbiting at around 500 km of altitude. We employ the Auroral Oval Detection (AOD) algorithm, a new technique we developed that allows to detect the crossing of the auroral oval using in-situ measurements of electromagnetic fields. This new technique combines a Median-Weighted Local Variance Measure and Iterative Filtering to automatically isolate high levels of electromagnetic activity caused by, e.g., particle precipitation and Field Aligned Currents (FAC) at auroral latitudes. AOD has been successfully applied to CSES-01 EFD data (Papini et al. Remote Sens., 15, 1568, 2023) to identify periods of high geomagnetic activity at auroral latitudes. Thanks to the versatility of AOD, we extended its application to magnetic field measurements taken by VFM (at a sampling frequency of 50Hz). We run the AOD algorithm over one year of VFM data from Swarm B. For all the ~5000 orbits we successfully detected crossing of the AO by the spacecraft on both hemispheres. For some orbits, we detected high level of activity in the polar caps, consistent with the results from the analogous survey run on one year of CSES-01 observations. Furthermore, we analyze the statistical properties of the magnetic and electric fluctuations in the detected intervals. This work represents the first step in the systematic study of the electromagnetic field properties at high latitudes, with many potential applications to space-weather studies.

104. A Decade with Swarm-Echo: Past Discoveries, Present Status, and Future Directions

Mr. Andrew Howarth[1], Dr. Andrew W. Yau[1], Dr. Paul A. Bernhardt[2], Dr H. Gordon James, Dr David J. Knudsen[1], Dr. Richard B. Langley[3], Dr. David M. Miles[4]

[1]University of Calgary, Calgary, Canada, [2]University of Alaska Fairbanks, Fairbanks, USA, [3]University of New Brunswick, Fredericton, Canada, [4]University of Iowa, Iowa City, USA

Ten years of data collection by the e-POP payload on Swarm-Echo (a.k.a. CASSIOPE) has resulted in a multi-terabyte data set of ionospheric measurements, including measurements of the local magnetic field, ions, electrons, radio waves, GPS signals, and aurora. The data set has enabled a host of detailed studies of magnetosphere-ionosphere coupling, including the Earth's magnetic field and related current systems, upper atmospheric dynamics, auroral dynamics, and related coupling processes among the magnetosphere, ionosphere, thermosphere, and plasmasphere, some of which will be highlighted in this presentation. We will also present some of the new Swarm-Echo data products and system tools available for use and look at the future direction of both the mission and the evolving data set.

105. Modelling Earth magnetic field

Assistant Professor Kuan Li[1]

[1]Macau Institute Of Space Technology and Applications, Macau, Macao

It is understood that the geomagnetic field, which is determined by a series of significant physical and chemical processes occurring within the region of Earth's core, mantle, crust, ocean and space, is stable and persistent in the large spatial scales in long term but strongly dynamical in smaller scales, especially during the period of the magnetic storms. Limited by the geomagnetic observations and the complexity of Earth's dynamical systems, the total geomagnetic field inversion is often performed for describing the geomagnetic field in the near Earth region using the observational data in the magnetic quiet time with the simplified (quasi-)linear assumptions for the contribution of the source terms.

One of the ultimate goals of the Macau satellite program is to utilise the Macau science satellite (MSS-1) and other high quality observational data, e.g., Swarm, to better understand the dynamics of Earth's geomagnetic systems and more accurately quantify the total field. In this presentation, I will discuss a possible approach to incorporate the conventional geomagnetic field models with more accurate physical constraints for simultaneously separating different source terms from the total field and probing the inner working of Earth magnetic systems, which are not directly measured.

106. Dipolar Spherical Elementary Current Systems (DSECS) toolbox for ionospheric current reconstructions

Dr. Heikki Vanhamäki[1], Sebastian Käki[2], Theresa Hoppe[2]

[1]University of Oulu, Oulu, Finland, [2]Finnish Meteorological Institute, Helsinki, Finland

The technique of spherical elementary current systems (SECS) is a powerful way to determine ionospheric and field-aligned currents (FAC) from magnetic field measurements made by low-Earth-orbiting satellites, possibly in combination with magnetometer arrays on the ground. The SECS method consists of two sets of basis functions for the ionospheric currents: divergence-free (DF) and curl-free (CF) components, which produce poloidal and toroidal magnetic fields, respectively.

The original CF SECS are only applicable at high latitudes, as they build on the assumption that the FAC flow radially into or out of the ionosphere. The FAC at low and middle latitudes are far from radial, which renders the method inapplicable at these latitudes. In the revised Dipolar version of the method (DSECS) the original CF SECS by including FAC that flow along dipolar field lines. This allows the method to be applied at all latitudes.

The DSECS method has been implemented in open source Python code and is included as part of the SwarmPAL toolbox (https://swarmpal.readthedocs.io/). We present the key features of the toolbox together with selected applications.

107. Energy transport in the magnetosphere–ionosphere system by Cluster and Swarm observations

Dr. Octav Marghitu[1], Dr. Dragos Consttantinescu[1], Dr. Vlad Constantinescu[1], Dr. Adrian Blagau[1], Dr. Horia Comisel[1]

[1]Institute for Space Sciences, Bucharest-Magurele, Romania

Energy transport in the magnetosphere–ionosphere (M–I) system can be seen as an intermediate stage between the energy source, ultimately in the solar wind, and the energy sink in the collisional ionosphere–thermosphere (I–T), by Joule heating and auroral luminosity. While this stage relies both on particle energy flux and on electromagnetic Poynting flux, the main contribution is expected to be achieved by Alfvénic Poynting flux, carried on in the polar regions along the magnetic field lines. With their polar orbits and multi-point measurements, Cluster and Swarm provide suitable high and low altitude platforms, respectively, in the magnetosphere and just above the collisional I–T, to investigate energy transport, assisted at times by ground data. Here we present sample results of a study that concentrates on conjugate Cluster–Swarm events and takes advantage of the long time overlap between the two missions, since the launch of Swarm at the end of 2013.

108. The performance of the Vector Field Magnetometer on the ESA Swarm mission

Prof. Jose M. G. Merayo[1]

[1]DTU Space, Lyngby, Denmark

Since the launch of the Swarm satellites on November 22nd 2013, the Vector Field Magnetometers (VFMs) have been providing continuously high-quality measurements of the Earth's vector magnetic field. The VFM is is located on the satellite boom on an optical bench co-mounted with the star tracker system. The VFM, which is a high-linear and stable magnetometer based on the fluxgate principle, is designed, built and calibrated at the Technical University of Denmark.
This paper presents the status of the instrument performance. In addition, it will be discussed the implications of the VFM's data quality into the scientific topics investigated by the Swarm mission which are based on the measurement spectral band.
This paper presents an overview of the instrument's performance status. Additionally, it discusses the implications of the VFM's data quality for the scientific objectives investigated by the Swarm mission, which are based on the various measurement spectral band.

109. Numerical analysis of charged particle interactions with rarefied gas flow

Martin Macak[1]

[1]TRL Space, Brno, Czech Republic, [2]AIT Austrian Institute of Technology GmbH, Vienna, Austria

Analysis of charged particle transport is an important point in various Space-oriented engineering and scientific fields such as spacecraft charging, detector design, development of ion propulsion systems, or material degradation predictions. Environmental conditions can significantly influence the trajectories of charged particles due to interactions with gas particles. In order to obtain precise results, it is necessary to calculate the gas flow field, as well as the trajectories of charged particles, and assess their interaction. As the altitude of the operation increases, the density of surrounding gas decreases, which significantly influences the environmental properties. Generally, there are two main approaches in numerical simulations of fluid flow. Computational Fluid Dynamics are applicable for higher pressures due to the continuity assumption. On the other hand, particle methods based on Monte Carlo are mainly used for modelling of gas flow in a vacuum as they become inefficient with the increase of particle interactions in higher pressures. As a result, there is still a gap between these two areas, in which the gas flow exhibits both properties. This paper presents an extension to Navier-Stokes equations for the calculation of slip and transitional flows in rarefied gases. The extension is based on applying slip flow boundary conditions and the introduction of gas properties, which are dependent on the Knudsen number. This model is coupled with a discrete element model for the possibility of tracking relativistic charged particles and their interactions with gas and solid matter. This model is then able to efficiently analyse both areas and their interactions simultaneously.

110. Identification of Aurora in FAI Swarm-E Images Using a U-Net Machine Learning Model

Mr. Andrew Howarth[1], Mr. Amit Kain[1], Dr. Matthew G. Finley[2,3], Dr. Andrew Yau[1]

[1]University of Calgary, Calgary, Canada, [2]Heliophysics Science Division, NASA Goddard Space Flight Center, Greenbelt, MD, USA, [3]Department of Astronomy, University of Maryland, College Park, MD, USA

The Swarm-Echo (a.k.a. CASSIOPE) satellite carries the e-POP payload, an instrument suite of eight instruments in an elliptical polar orbit spanning 320-1500 km altitude. Part of e-POP, the Fast Auroral Imager (FAI) captures images of the aurora in near-infrared (650-1000 nm) wavelengths at one second cadence, collecting over 1.7 million images to date. In this study, we use a Semantic Segmentation based U-Net model to predict the appearance of various classifications of aurora present in the images. We manually labelled individual pixels from a diverse set of 4091 FAI images into seven different classes; no aurora, contaminated, diffuse, discrete, arc, ambiguous, and vignette. We use a slightly modified version of U-Net to train the model and use various post-processing techniques to create tags for individual satellite passes of ~10 minutes each. Overall, the trained model was able to predict 74% of the pixels accurately for unseen data.

111. Radial shear in the core surface flow from Swarm data

Dr Dominique Jault[1], Ilya Firsov, Nicolas Gillet[1], Thea Lepage, Mioara Mandea

[1]CNRS & University Grenoble Alpes, Grenoble, France

We model the Earth's mantle as an electrical insulator except for a thin conducting layer abutting the core. Continuity between the three components of the magnetic secular variation on either side of the interface between the conducting and insulating parts of the mantle yields a relationship between the flow at the core surface u, the radial shear in the flow r du/dr and a term τ_G du/dt function of the time derivative of the flow (Firsov et al., 2023). Here, τ_G is a time scale, which depends linearly on the mantle conductance. The relative importance of the different terms in this equation depends on the time scales we can access. In this context, satellite magnetic data are crucial since they allow us to investigate rapid changes in the flow. In addition, we rely on numerical simulations of the geodynamo to estimate representativity errors arising from the interactions between small-scale velocity and magnetic fields. In these simulations, we have to account for the magnetic field induced in the viscous boundary layer attached to the core-mantle interface. The strength of this field depends on the magnetic Prandtl number, which is much larger in most geodynamo simulations than in the Earth's core. Assuming axial invariance of the flow in the core interior let us infer at the core surface the radial shear in the flow from the flow. Then, we are left with only one unknown, the mantle conductance. Together with seismological and tidal models of the Earth's mantle, constraining the mantle conductance may be crucial to infer the mineralogy of the lowermost Earth's mantle.

112. Flow at the top of the free stream in geodynamo simulations

Dr. Dominique Jault[2], Ilya Firsov[1], Nicolas Gillet[2], Mioara Mandea[3]

[1]CNES & University Grenoble Alpes, Grenoble, France, [2]CNRS & University Grenoble Alpes, Grenoble, France, [3]CNES, Paris, France

We rely on geodynamo simulations to supplement the information obtained from geomagnetic models (built from satellite and observatory data) with prior knowledge of the velocity and magnetic fields in the Earth's core. This has allowed us to handle representativity errors in core surface flow estimations. In this context, stress-free dynamo simulations have proven convenient since the surface flow can be directly extracted as the flow at the core-mantle boundary. Indeed, prior information on the state of the core has been gathered from such simulations. However, the appropriate boundary condition for the flow at the core-mantle boundary is no slip instead. In this study, we obtain the flow at the top of the free stream in no slip simulations from an investigation of the viscous -Ekman-Hartmann- boundary layer attached to the core-mantle interface. At each location within this layer, the velocity and magnetic fields can be expressed as a function of their value at the top of the free stream. We set up an inverse problem and obtain a unique definition of these quantities. We can use it to build the prior information that we need to estimate the flow at the top of the free stream in the Earth's core and possibly the radial shear in the flow.

113. Dynamical Complexity in Swarm-Derived Storm and Substorm Activity Indices Using Information Theory: Further Evidence for Interhemispheric Asymmetry

Constantinos Papadimitriou[1], Dr Georgios Balasis[1], Dr Adamantia Zoe Boutsi[1], Dr. Stelios M. Potirakis[2], Prof. Ioannis A. Daglis[3], Dr. Omiros Giannakis[1]

[1]National Observatory Of Athens, Penteli, Greece, [2]University of West Attica, Athens, Greece, [3]Hellenic Space Center, Athens, Greece

In November 2023, the ESA Swarm constellation mission celebrated 10 years in orbit, offering one of the best-ever surveys of the topside ionosphere. Among its achievements, it has been recently demonstrated that Swarm data can be used to derive space-based geomagnetic activity indices, like the standard ground-based geomagnetic indices, monitoring magnetic storm and magnetospheric substorm activity. Given the fact that the official ground-based index for the substorm activity (i.e., the Auroral Electrojet – AE index) is constructed by data from 12 ground stations, solely in the northern hemisphere, it can be said that this index is predominantly northern, while the Swarm-derived AE index may be more representative of a global state, since it is based on measurements from both hemispheres. Recently, many novel concepts originated in time series analysis based on information theory have been developed, partly motivated by specific research questions linked to various domains of geosciences, including space physics. Here, we apply information theory approaches (i.e., Hurst exponent and a variety of entropy measures) to analyze the Swarm-derived magnetic indices around intense magnetic storms. We show the applicability of information theory to study the dynamical complexity of the upper atmosphere, through highlighting the temporal transition from the quiet-time to the storm-time magnetosphere, which may prove significant for space weather studies. Our results suggest that the spaceborne indices have the capacity to capture the same dynamics and behaviors, with regards to their informational content, as the traditionally used ground-based ones. A few studies have addressed the question of whether the auroras are symmetric between the northern and southern hemispheres. Therefore, the possibility to have different Swarm-derived AE indices for the northern and southern hemispheres respectively, may provide, under appropriate time series analysis techniques based on information theoretic approaches, an opportunity to further confirm the recent findings on interhemispheric asymmetry. Here, we also provide evidence for interhemispheric energy asymmetry based on the analyses of Swarm-derived auroral indices AE North and AE South.

114. Efficient equivalent source processing of aeromagnetic and satellite magnetic data – a physics-based multi-layer approach

Dr. Wolfgang Szwillus[1], Dr. Björn Heincke[2], Msc. Judith Freienstein[1], Prof. Dr. Jörg Ebbing[1]

[1]Kiel University, Kiel, Germany, [2]GEUS, Copenhagen, Denmark

Combining aeromagnetic surveys with satellite magnetic data can provide a detailed picture of Earth's geomagnetic anomalies. However, reconciling different aeromagnetic surveys can be challenging, especially if legacy data (due to e.g. lack of GPS positioning, no or improper base station corrections) are involved and the datasets might contain processing inconsistencies, which only become apparent when different surveys are combined. Satellite data are commonly used to replace the longest wavelengths of aeromagnetic compilations, but this suffers from spectral distortions, especially on regional spatial scales If Fourier-based techniques are applied that ignore the sphericity of the Earth.

We present a new equivalent source technique based on magnetic dipoles suitable for merging aeromagnetic data from several surveys as well as satellite data. A fundamental challenge for any equivalent source technique is the computational demand that results from a combination of large number of data, and a high resolution and large spatial extent of the resulting model. Both high resolution and large spatial extent are necessary to make full use of the information content of aeromagnetic surveys.

To facilitate the use of large datasets, we make use of two physics-based strategies. Firstly, we use several layers of equivalent dipoles at different depths. Beginning with a deep layer with a relatively wide spacing, we iteratively use shallower layers, and fit the equivalent sources of this layer to the residual of the previous steps. Secondly, we exploit the $1/r^3$ dependence of the magnetic field to reduce the computational demand. Two alternative ways of achieving this have been implemented: Either, the study area is divided into overlapping blocks and the equivalent source technique is applied independently in each block, or the entire sensitivity matrix is approximated by a sparse matrix based where only entries are considered, if distances between sources and data points are below specified thresholds.

We combine the aeromagnetic surveys with satellite data by fitting a second set of equivalent sources to the satellite magnetic data . Then, we use a semi-analytical expression of the band-limited response of a dipole in terms of spherical harmonics to derive a final field, which is based on both the aeromagnetic and satellite-derived dipoles. This technique circumvents spherical harmonic analysis. Alternatively, spherical harmonic analysis can be used to replace the longest wavelengths.

In a companion presentation by Heincke et al., we use our novel approach to generate a new aeromagnetic compilation of Greenland.

115. Mission Synergies: Lessons learned from Swarm radiation pressure modelling for improving GOCE neutral thermosphere crosswind data products.

Ms. Natalia Hladczuk[1], Sabin Anton[1], Dr.ir. Jose van den IJssel[1], Dr. Christian Siemes[1], Prof.dr.ir. Pieter Visser[1]

[1]Delft University Of Technology, Delft, Netherlands

The characteristics of the neutral thermospheric wind play an important role in understanding the coupling of Earth's thermosphere-ionosphere and in improving models used in space operations. The Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) satellite which operated at an altitude of ~250km, provided thermosphere crosswind data during most of its operational lifetime from 2009 to 2013.

The accuracy of thermospheric wind data sets derived from satellite accelerations is coupled with uncertainties in the aerodynamic and radiation pressure modeling. Currently produced GOCE crosswind datasets employ high-fidelity geometry. However, they do not account for the thermal emission of the satellite. Considering its large surface area and the extreme temperature variations the GOCE satellite experienced, thermal acceleration plays a pivotal role, especially during eclipse transitions.

In our approach to calculating the thermal emission, we use the in-situ measurements from GOCE thermistors that monitor the surface temperature. For the satellite wings, the thermistors were located on the outer surfaces facing cold space (away from the Sun), and for the body-mounted solar arrays, they were placed underneath the panels. Therefore, there are no temperature readings that reflect the sunward panels' surface temperatures, which could be used for modeling the acceleration due to thermal emission. We tackle this issue using similarities between Swarm's and GOCE's mission design. In both cases, the satellites were equipped with solar panels characterized by the honeycomb structure on which the Kapton foil and highly efficient triple-junction Gallium Arsenide (GaAs) solar cells were mounted. However, contrary to GOCE, the thermistors were placed on top of the panels in the case of Swarm. Moreover, the Swarm mission's documentation also provides better characterized thermo-optical surface properties. Using the similarities between the two missions, we can fit the Swarm thermal model to learn valuable lessons for GOCE radiation pressure and thermal emission modeling.

Getting insight into selecting the realistic thermal model's parameters is expected to significantly improve the crosswind estimates for GOCE. Furthermore, this investigation may lead to re-evaluating the current accommodation coefficient choice and possibly affect the neutral thermosphere density estimates.

116. Noise features of the MSS-1 vector magnetometer

Dr. Fan Yin[1], Hermann Lühr[2], Sishan Song[1], Qing Yan[3], Yi Jiang[3]

[1]Department of Space Physics, Electronic Information School, Wuhan University, Wuhan, China, [2]GFZ German Research Centre for Geosciences, Section 2.3, Geomagnetism, Potsdam, Germany, [3]State Key Laboratory of Lunar and Planetary Sciences, Macau University of Science and Technology, Macao, China

The Macau Science Satellite-1 (MSS-1) is designed to study the spatial and temporal variation of the Earth's magnetic field in circular orbits with an inclination of 41° and altitude about 450km. As the previous CHAMP mission and the current SWARM missions, the satellite carries a high-precision vector magnetometer and a stellar compass mounted rigidly together on an optical bench. 50 Hz sample rate of the magnetometer allows us to investigate all signals from DC to Nyquist frequency. A frequency sweep from the Nyquist frequency down to zero and up again, which was found in CHAMP magnetic data as well, occurs frequently, but shows some different features.

117. NASA's Geospace Dynamics Constellation—Providing the first Systematic Measurements of Global Magnetospheric Energy Inputs and Ionosphere-Thermosphere Responses

Prof. Jeff Thayer[1], Dr. Douglas Rowland[2], Dr. Katherine Garcia-Sage[2], Dr. Larry Kepko[2], Dr. Rebecca Bishop[3], Dr. Yue Deng[4], Dr. Philip Anderson[5], Dr. Mark Moldwin[6], Dr. Olga Verkhoglyadova[7], Dr. Laila Andersson[1], Dr. Mehdi Benna[2], Dr. Dan Gershman[2]

[1]University of Colorado, Boulder, United States, [2]NASA/GSFC, Washington DC, United States, [3]The Aerospace Corporation, Los Angeles, CA, USA, [4]University of Texas at Arlington, Arlington, Texas, USA, [5]University of Texas at Dallas, Dallas, TX, USA, [6]University of Michigan, Ann Arbor, MI, USA, [7]Jet Propulsion Lab, Pasadena, CA, USA

The Geospace Dynamics Constellation (GDC) is NASA's next strategic Living With a Star mission. GDC's goals are: 1) Understand how the high-latitude ionosphere-thermosphere system responds to variable solar wind/magnetosphere forcing; and 2) Understand how internal processes in the global ionosphere-thermosphere system redistribute mass, momentum, and energy. Planned for launch by the end of the decade, GDC will use six identical observatories, each identically instrumented to fully characterize the magnetospheric drivers of the I-T system as well as the global response of the ionized and neutral gases. GDC will do this with a series of orbital configurations that will enable it to study the widest range of spatial and temporal scales to date, ranging from hundreds of kilometers and several seconds to tens of minutes, and extending through the regional to the global scale. This talk presents GDC's current status, measurement capabilities, sampling scheme, and model development efforts and show how GDC will fit into the larger Heliophysics ecosystem, by 1) obtaining critically needed scientific observations; 2) providing a source for real-time space weather and situational awareness, as well as retrospective studies to further the science of space weather; 3) serving as a "strategic hub" for other space-based and ground-based efforts that want to leverage GDC to perform complementary science.

To get the most benefit from GDC's observations, it will be critical to identify partnerships with other research efforts in the ITM and Geospace arenas, including those utilizing space-based, ground-based, or theoretical investigations. We particularly would like to discuss with groups who are planning or considering observational campaigns during the GDC era, to find ways to leverage GDC observations to do synergistic science that could not be done otherwise.

118. Initial Study of Novel Quantum Diamond-based Sensors aboard the ISS for Future Earth Observation Missions

Dr. Jaroslav Hruby[1,2], Yarne Beerden[1], Boo Carmans[1], Dries Hendrikx[1], Remy Vandebosch[1], Prof. dr. Anna Ermakova[1,3], Prof. dr. Milos Nesladek[1,2]

[1]IMO, Hasselt University, Diepenbeek, Belgium, [2]IMOMEC, IMEC vzw, Diepenbeek, Belgium, [3]BIRA-IASB, Brussels, Belgium

Measuring magnetic fields in space is essential for studying Earth's core and crustal processes as well as monitoring of space weather. Current sensors face challenges of complying with modern mission requirements related to size, weight, and power restrictions while demanding highly sensitive and stable systems. Novel quantum technologies are being investigated to overcome limitations of classical magnetometers for future Earth Observation missions. A promising platform is the Nitrogen-Vacancy (NV) center in diamond. These sensors have unique properties, such as broad dynamic range (linear up to 0.1 T) and bandwidth (DC-MHz), high sensitivity (theoretically down to fT/√(Hz)) in both scalar and vector measurement modes. NV sensors can also operate at a wide range of temperatures (including room temperature), acting simultaneously as an independent temperature probe. Additionally, diamond is inherently radiation-resistant, thermally stable, and can withstand a wide range of pressures making them ideal candidates for space magnetometers.

Here, we report on the scientific results of the OSCAR-QUBE mission, an initial study of quantum diamond-based NV magnetometer developed by an interdisciplinary student team aboard the International Space Station, within ESA Education programme ‘Orbit Your Thesis!’. The team was selected for the programme in April 2020. After the design, development, and testing phase, the device was installed aboard the ISS inside the ICECubes Facility in the Columbus module in September 2021. The device was decommissioned in August 2022. The resulting device was miniaturized to 1U (10x10x10 cm^3), 420 g, 5 W of peak power consumption, with a sensitivity of < 300 nT/√(Hz).

Successful operation of a quantum diamond-based magnetometer tested in low Earth orbit for nine months is presented. Both the sensor performance and measurement parameters remained stable. The acquired data was compared to the CHAOS-7 Earth’s magnetic field model and demonstrated close correlation. The deviation of the sensor was evaluated and comparison exhibited no significant degradation over the mission duration. Resulting magnetic field maps contain information of both total and vector components of Earth’s magnetic field. Additionally we demonstrated the temperature sensing capabilities of the diamond based sensor.

This study points towards the viability of diamond-based sensors as a compact and stable sensing solution for future space applications. An upcoming iteration of the diamond-based sensor will be tested aboard the inaugural flight of Ariane 6 within the ESA YPSat mission. It will provide the opportunity to further test this novel technology under space conditions.

119. Swarm and its role in understanding a 6-year oscillation in the Earth's system

Mrs. Mioara Mandea[1], Anny Cazenave, Veronique Dehant, GRACEFUL

[1]Cnes, Paris Cedex 01 , France

Oscillations in the length of day have been observed for periods around 6 years and toughly attributed to dynamical processes in the fluid outer core that also origin decadal oscillations and secular variation in the geomagnetic field, as obtained from Swarm data. Recently, a 6-year cycle has also been revealed in some climatic parameters (e.g., sea level, surface temperature, precipitation, land hydrology, land ice, and atmospheric angular momentum). Interestingly, oscillations in the terrestrial water storage are also detected at periods around 6 years in GRACE and GRACE-FO gravity data.

Here, we report these observations and underline the Swarm role understanding the dynamical processes that originate in the deep Earth's interior. The question of a potential link between the deep Earth's interior processes, length of day and climatic fluctuations at the 6-year period is also addressed.

120. Spatial and temporal characteristics of ionospheric perturbations over regions of major thunderstorm cells

Dr. Ewa Slominska[1]

[1]Obsee, Warsaw, Poland

Lightning can be considered as one of the most common examples of natural hazard phenomena. Up to 2000 thunderstorms are active over the surface of the Earth at any given time, with an average of roughly 45 lightning discharges occurring every second, in the most active lightning spots over the Americas, Africa, and South-East Asia. Since lightning discharges radiate intense electromagnetic (EM) pulses, from a few Hz to hundreds of MHz, a small fraction of these phenomena is registered with the ASM and VFM magnetometers onboard Swarm. 10 years of Swarm registrations proved capabilities of magnetometers on-board the constellation to detect magnetic field perturbations triggered by lightning activity, and in general the most common manifestation of such disturbances is in the form of sferics and whistlers. In case of the VFM registrations, the majority of detected cases depicts signals which were triggered by special class of lightning activity, so called transient luminous events (TLE), occurring above a large thunderstorm at stratospheric and mesospheric altitudes. This finding gives direct experimental confirmation of a link between thunderstorms and leakage of magnetic field fluctuations to the upper ionosphere.
Extended analysis revealed that in certain regions we may observe additional effects of thunderstorm activity, such as an amplification of periodics fluctuations of magnetic field, accompanied with small changes in the plasma parameters. Unlike plasma bubbles, here fluctuations of electron density are more subtle (less than 10% with respect to the averaged electron density) and instead of equatorial regions, they more often occur at mid-latitudes. Spectral analysis reveals that typical frequencies of observed fluctuations are below 3 Hz, suggesting similarities with Pc1-3 waves, but also indicates that such range is important for excitation of the ionospheric Alfvén resonator (IAR). The goal of the study is to discuss conditions under which thunderstorm activity can stimulate ULF hydromagnetic waves.

121. Pattern Recognition & Machine Learning Techniques for Automated Classification of Signals in Swarm Time Series

Dr Georgios Balasis[1], Alexandra Antonopoulou[1,2], Constantinos Papadimitriou[1,2], Dr Zoe Boutsi[1,2], Prof Ioannis A. Daglis[1,2,3], Dr Omiros Giannakis[1]

[1]National Observatory of Athens, Athens, Greece, [2]National and Kapodistrian University of Athens, Athens, Greece, [3]Hellenic Space Center, Athens, Greece

With 10 years of Swarm data currently available, the employment of big data analysis techniques is essential to fully deploy the scientific discovery capabilities of this unique data set. Ultra-low frequency (ULF) magnetospheric plasma waves play a key role in the dynamics of the Earth's magnetosphere and, therefore, their importance in space weather phenomena is indisputable. Magnetic field measurements from recent multi-satellite missions (e.g., Cluster, THEMIS, Van Allen Probes and Swarm) are currently advancing our knowledge on the physics of ULF waves. In particular, Swarm satellites, one of the most successful missions for the study of the near-Earth electromagnetic environment, have contributed to the expansion of data availability in the topside ionosphere, stimulating much recent progress in this area. Swarm also plays a key role in the study of Equatorial Spread-F (ESF) events, which are post-sunset ionospheric plasma instabilities, also called plasma bubbles, causing a degradation of the GNSS signals at equatorial latitudes. Coupled with the new successful developments in artificial intelligence (AI), we are now able to use more robust approaches devoted to automated ULF wave and ESF event identification and classification. The goal of this effort is to use a popular machine learning method, widely used in Earth Observation domain for classification of satellite images, to solve a space physics classification problem, namely to identify ULF wave and ESF events using magnetic and electric field data from Swarm. We construct a Convolutional Neural Network (ConvNet) that takes as input the wavelet spectrum of the Earth's magnetic field variations per track, as measured by Swarm, and whose building blocks consist of two alternating convolution and pooling layers, and one fully connected layer, aiming to classify ULF wave and ESF events within four different possible signal categories: (1) Pc3 wave events (i.e., frequency range 20–100 MHz), (2) background noise, (3) false positives, and (4) plasma instabilities. Our preliminary experiments show promising results, yielding successful identification of more than 97% accuracy. The same methodology can be easily applied to identify higher frequency plasma waves (i.e., Pc1 at 0.2–5Hz), as well as magnetometer data from other satellite missions and ground-based arrays. To leverage the corresponding potentials of state-of-the-art machine learning and artificial intelligence techniques, in the future, we will pursue a two-fold approach to studying ionospheric plasma instability consisting of a classification problem (for systematically identifying plasma instabilities in the existing data along with characteristic precursors in the dynamics of magnetic field variations) and a regression problem (for developing a possible real-time forecasting system for ESF events). For this purpose, we will test different architectures of artificial neural networks along with flexible nonlinear statistical forecast models.

122. Scaling Features of Magnetic Field Fluctuations in the Auroral and Polar Ionosphere

Dr. Simone Mestici[1], Fabio Giannattasio[2], Giuseppe Consolini[3], Paola De Michelis[2], Tommaso Alberti[2], Francesco Berrilli[4]

[1]University of Rome La Sapienza, Rome, Italy, [2]National Institute of Geophysics and Volcanology (INGV), Rome, Italy, [3]National institute of Astrophysics and Planetary Sciences (IAPS), Rome, Italy, [4]University of Rome Tor Vergata, Rome, Italy

The turbulent and intermittent nature of plasmas plays a fundamental role in the coupling mechanisms and energy exchange occurring between the solar wind and the Earth's magnetosphere-ionosphere system. In particular, moderate and severe solar and geomagnetic conditions lead to a plethora of complex phenomena such as ionospheric irregularities and the amplification of magnetospheric and ionospheric currents like the field-aligned currents (FACs). The structure and dynamics of these currents have relevant implications in understanding ionospheric heating and electric and magnetic field fluctuations in the auroral and polar environments.

In this scenario, we present preliminary results of a study aimed at investigating the nature of small-scale fluctuations characterizing the ionospheric magnetic field in response to different geomagnetic conditions. We use high-resolution (≥50Hz) magnetic data from the ESA's Swarm mission flying at about 450 km altitude for an ensemble of high-latitude crossings to probe the scaling features of magnetic field fluctuations at spatial scales (≤150m) still poorly explored. Structure function scaling analysis is used to investigate the statistical properties of fluctuations, which provides information on scaling features and the intermittent nature of turbulent signals. The primary goals of this work are to: i) investigate the power density distribution of fluctuations across a wide range of spatio-temporal frequencies; ii) characterize the persistence of fluctuations and gain information on the existence of localized spatial structures; iii) get insights into intermittency/anomalous scaling, which reflects the inhomogeneous distribution of energy at the smaller scales, and its dependence on magnetic local time sectors; and iv) compare the magnetic field scaling features between the region where FACs flow and the polar cap. The findings will be discussed in light of the literature.

123. 10 years of Swarm PDGS Operations: Lessons Learned

Mr. Antonio de la Fuente[1], Mr Alessandro Maltese[2], Ms Livia D'Alba[3], Mr Luca Mariani[2], Ms Francesca Gabrieli[2], Mr Danilo Parente[2], Mr Antonio Biscuso[2]

[1]European Space Agency, Frascati, Italy, [2]SERCO c/o ESA, Frascati, Italy, [3]RHEA c/o ESA, Frascati, Italy

The Swarm Payload Data Ground Segment (PDGS) is the mission element responsible for data processing, archiving and dissemination, product quality control, calibration and performance monitoring. The Swarm PDGS functionalities are implemented as a combination of dedicated systems and teams and shared services. It has been performing without major problems since its inception, fulfilling all mission requirements and representing a major success for the Swarm mission.

Contrary to the common perception that Operational Ground Segments are static and conservative by nature, the architecture of the Swarm PDGS has been constantly evolving to respond to new operational and science requirements, to incorporate new science products, and to improve the robustness, maintainability and efficiency of the current system using the latest available techniques.

This poster summarises the efforts of the Swarm DPGS Ops support team over the last decade in several areas: The evolution and streamlining of the system architecture to make it maintainable in the long term, the migration from a physical to a virtual infrastructure, the flexible provision of the required storage and processing power for the full mission reprocessing campaigns, the improvements in the monitoring and reporting subsystems, the simplification of the user access to the data, the integration of additional new data products coming from the Swarm DISC Processing Centres and the other missions, the strengthening and enhancement in the area of system security, the implementation of the FAST platform, the changes in the contractual approach, etc... Finally, this contribution will also provide a synthesis of the main lessons learned during this period.

124. The Time-Frequency Analysis (TFA) Toolbox: a Versatile Processing Tool for the Recognition of Magnetospheric and Ionospheric Signals in Swarm Time Series

Dr Georgios Balasis[1], Constantinos Papadimitriou[1,2], Dr Zoe Boutsi[1,2], Alexandra Antonopoulou[1,2], Dr Omiros Giannakis[1], Dr Ashley Smith[3]

[1]National Observatory of Athens, Athens, Greece, [2]National and Kapodistrian University of Athens, Athens, Greece, [3]University of Edinburgh, Edinburgh, UK

The ongoing Swarm mission of the European Space Agency (ESA) provides an opportunity for a better knowledge of the near-Earth electromagnetic environment, including investigations of ultra-low frequency (ULF) wave and Equatorial Spread-F (ESF) events. The Time-Frequency Analysis (TFA) tool is a processing tool established for deriving Pc1 (0.2–5 Hz) and Pc3 (20–100 mHz) wave indices. The tool includes both a graphical interface as well as a dedicated back end that can be used to perform wavelet analysis and visualize the results for both Pc1 and Pc3 waves, using both Swarm magnetic Level 1b 50 Hz and 1 Hz data. Following recommendations from the Advisory Board of the Swarm Data, Innovation and Science Cluster (Swarm DISC) the tool has been further developed and generalized to accommodate analysis of other types of time series from both satellite and ground station measurements. In particular, the resulting TFA toolbox provides users with the capabilities of studying different wave types (e.g. compressional waves, Alfvén waves, etc.), various magnetic field components (e.g. in Mean Field Aligned – MFA coordinates), and other geophysical measurements (e.g. electric field, plasma parameters). The TFA toolbox is also able to detect external source signals, e.g. due to plasma instabilities like post-sunset ESF events, and artificial disturbances (anomalies), e.g. spikes, jumps. It is also possible to use data from ground stations in a consistent format, e.g. 1 Hz magnetic observatory data as available in the virtual research service - VirES for Swarm. Moreover, integration of the TFA toolbox into the VirES platform is currently under development. This presentation aims to demonstrate the unique capabilities of the Swarm DISC TFA toolbox, including the recent update of its routines to support the use of the new Swarm FAST data and a first attempt to calculate ULF wave derived radiation belt radial diffusion coefficients (DLL) both from FAST and operational data. The latter may open new research horizons for the mission because it could contribute to the understanding of how and why the radiation belts change during active geomagnetic periods, which is a key goal of the space weather community.

125. Swarm-VIP-Dynamic: variability, irregularities, and predictive capabilities for the dynamic ionosphere based on the Swarm measurements

Prof. Wojciech Miloch[1], Dr. Yaqi Jin[1], Dr Daria Kotova[1], Dr Alan Wood[2], Dr Gareth Dorrian[2], Dr Lucilla Alfonsi[3], Dr Luca Spogli[3], Dr Rayan Imam[3], Dr Eelco Doornbos[4], Dr Kasper van Dam[4], Dr Mainul Hoque[5], Dr Jaroslav Urbar[6]

[1]University Of Oslo, Oslo, Norway, [2]University of Birmingham, Birmingham, UK, [3]Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy, [4]The Royal Netherlands Meteorological Institute (KNMI), Den Haag, Netherlands, [5]German Aerospace Center (DLR), Neustrelitz, Germany, [6]Institute of Atmospheric Physics CAS, Prague, Czech Republic

The drivers of Earth's ionosphere are highly variable, leading to variability and structuring of the ionosphere. Coupling of the ionosphere with the Earth’s magnetosphere and the solar wind, as well as to the neutral atmosphere, make the phenomena in the ionosphere highly dynamic, which can be seen at different spatiotemporal scales, ranging from planetary down to decameter spatial scales, and from solar cycle down to daily, hourly, and even minutely temporal variations. Thus, modelling of the whole ionosphere and capturing its full dynamic range is a challenging task.

Satellite-based measurements can form a basis for ionospheric models where various spatiotemporal scales can be addressed, and they can significantly contribute to our efforts within the context of space weather modeling. The Swarm mission has been successful in providing high-quality in situ data over many years, allowing for both space weather and climatological studies. Recently, with the Swarm-VIP models it has been demonstrated that the Swarm mission can successfully address the ionospheric variability at larger scales in relation to geophysical proxies. The new Swarm-VIP-Dynamic model focuses on the variability, irregularities, and predictive capabilities for the dynamic ionosphere. In the project, we develop a suite of models for capturing the ionosphere structuring and dynamics at various scales, including small scales. In addition to the Swarm data, we use a significant number of datasets from other satellites and from ground-based instruments for validation and to explore the added value of space instrumentation with various observation and sampling characteristics. We also test the feasibility of the models to be used in a real-time environment. We present the Swarm-VIP-Dynamic project, its background and model concepts, initial results, as well as prospects of further development in the context of space weather and predicting of ionospheric space weather effects.

126. Enhanced ionospheric density variability and RTK positioning uncertainty at dayside subauroral latitudes

Dr. Stephan Buchert[1], Dr. Martin Håkansson[2], Elliot Lindhe[3]

[1]Swedish Institute of Space Physics, Uppsala, Sweden, [2]Lantmäteriet, Gävle, Sweden, [3]Adolfsbergsskolan, Knivsta, Sweden

Enhanced density variability is known to occur related to auroral phenomena, mostly at dusk, on the night side and dawn, to polar cap patches, and to the post-sunset equatorial region. Surprisingly we found that the plasma density variability is statistically increased at subauroral latitudes, about 54-61 degrees, in the 1-2 hours around local noon. The Swedisch cadastral office (Lantmäteriet) offers satellite based positioning, called SWEPOS, which is using RTK (Real Time Kinematic) and reference stations covering the whole of Sweden. The SWEPOS uncertainty is about 1 cm. We found that this uncertainty statistically increases to a few centimeters in the hours around noon also down to the middle and southern parts of Sweden (Svealand and Götaland). We suggest that both phenomena are causally related.

127. Automatic detection of Pc1 pulsations in Swarm's high-frequency magnetic measurements

Tamás Bozóki[1,2], Balázs Heilig[1,2]

[1]HUN-REN Institute of Earth Physics and Space Science, Sopron, Hungary, [2]ELTE Eötvös Loránd University, Institute of Geography and Earth Sciences, Department of Geophysics and Space Science, Budapest, Hungary

Pc1 pulsations cover the 0.2-5 Hz frequency range. This frequency range is generally accepted to include waves that are referred to as electromagnetic ion cyclotron (EMIC) waves based on their excitation mechanism. In general, EMIC waves are generated as transverse, left-handed polarized waves, and reach the ionosphere by propagating along the geomagnetic field lines. In the ionosphere the initially transverse waves also generate compression waves, which can propagate long distances parallel to the Earth's surface. EMIC waves play an important role in the Earth's magnetosphere, as they can precipitate relativistic electrons from the outer radiation belt and energetic protons from the ring current. Hereby, their observation provides important information about the energy coupling between the ionosphere and the magnetosphere as well as the particle dynamics inside the Earth's magnetosphere.

In this contribution, a new data product characterizing Pc1 pulsations detected in Swarm's high-frequency magnetic measurements is described and the statistical properties of the detected Pc1 events are reported. The automatic detection and characterization of Pc1 geomagnetic pulsations consists of five main steps. First, the high-frequency magnetic measurements are transformed into a field-aligned coordinate system. Then, the spectrograms of the field components are calculated and different types of noise are removed from the spectrograms. In the third step, Pc1 candidate events are determined based on peak finding and the coherence of the field components. Next, individual Pc1 events are identified and extracted from the spectrograms. Finally, the extracted individual events are characterized by the following quantities: start time, end time, duration, average frequency, average width, average prominence, average intensity, average peak intensity, average rate of frequency change. The statistical characteristics of the detected events will be compared with previously published results. Finally, we will also discuss what research directions this new product could be used for in the future.

128. Short-term regional ionosphere imaging at mid- and high-latitudes: A four-dimensional ensemble-based variational approach

Dr. Nicholas Ssessanga[1], Prof. Wojciech Jacek Miloch[1], Dr Daria Kotova[1], Dr. Yaqi Jin[1]

[1]4D Space, University of Olso, Oslo, Norway

At 4DSpace, we have in-house developed and rigorously evaluated a robust short-term forecasting method—Strong Constraint Four-Dimensional Ensemble-Based Variational (SC4DEnVar). The scheme initializes from (IRI-2016) and utilizes Gauss Markov filtering to forward propagate electron densities (30-min), ensuring their adherence to a log-normal distribution for the requisite positive definiteness of ionospheric density. Preliminary assimilation is only with ubiquitous Global Navigation Satellite System (GNSS) observables from ground-based receivers. The focus is on moderately quiet mid-latitudes and high-latitudes, where prevalent ionospheric nonlinearities, absent in models like IRI, are observed. We Verify the reconstructions with independent data from SWARM satellites, ground-based ionosondes, and satellite radio occultations (RO). Results indicate that improvements are fairly adequate during the quiet period- notably, SC4DEnVar effectively incorporates new information, such as the time expansion of the tongue of ionization, previously absent in the background model. Using SWARM and RO data, we find SC4DEnVar to significantly improve the 3D-electron density picture, specifically in the F-region, remote areas and during severe conditions. In addition to computational efficiency and maintainability, these results support SC4DEnVar as a candidate for precise short-time regional forecasting.

129. The Swarm data and software landscape in 2024 and beyond

Dr. Ashley Smith[1]

[1]University of Edinburgh, Edinburgh, United Kingdom

Swarm products can be found and utilised through a number of different channels and mechanisms. This presentation reviews the current situation and looks toward the future where we expect more focus on sustainable software tools, and on greater interconnectivity with other data sources and tools.

The revamped Swarm data handbook acts as a portal to robustly document products and links to access mechanisms: file server, VirES graphical interface, notebook, and HAPI link. We expect to evolve this and ensure it can be linked to wider data discovery tools. The VirES service continues to improve and extend (see the dedicated presentation), while there is also a growth in community-built tools that utilise the VirES platform (e.g. SwarmPAL). In connection with this, adoption of the HAPI specification within VirES is also opening more opportunities from beyond the Swarm community.

These works contain contributions from EOX IT Services and many people across ESA, Swarm DISC, and the wider community.

130. Co-estimation of geomagnetic field and magnetometer calibration parameters using data from Swarm-Echo

Mr. Robert Broadfoot[1]

[1]University Of Iowa, Iowa City, United States

Swarm-Echo, formerly CASSIOPE/ePOP, was adopted into the Swarm constellation in 2018 to take advantage of its highly elliptical orbit and instrument suite, which includes two fluxgate magnetometers (MGF) on a shared boom, that complements the science performed by the Swarm constellation. Upon its adoption into the constellation, an effort began to improve the accuracy and viability of the measurements provided by ePOP which included but was not limited to performing an in-situ calibration of MGF. MGF, while used primarily for scientific measurements not navigation, shares a similarity to satellites with so-called platform magnetometers as it does not contain an onboard calibration reference such as the absolute scalar magnetometer (ASM) present on the other satellites in the Swarm constellation. An initial attempt to calibrate the fluxgate magnetometers was performed in 2021 using the most recent distributed version of the Chaos magnetic field model. However, it has been shown in other instances that reliance on a fixed magnetic field model for calibration can introduce a bias into the calibration results. Instead, we choose to adopt a co-estimation method similar to the method used to calibrate Cryosat-2 which results in obtaining both the calibration parameters and the magnetic field model parameters for the internal and external geomagnetic field using the mathematics of the Chaos model and in-situ magnetometer measurements from the Swarm satellites including Echo along with measurements from Cryosat-2 and data from ground-based magnetic observatories spanning the years 2014-2021. These initial results of the co-estimation of the calibration parameters and magnetic field model parameters represent a culmination of the effort to improve the scientific viability of the fluxgate magnetometer data aboard Swarm-Echo.

131. Statistical study of the variability of ionospheric parameters measured by Swarm satellites

Dr. Daria Kotova[1], Dr Yaqi Jin[1], Dr. Wojciech Miloch[1]

[1]Department of Physics, University of Oslo, Oslo, Norway

The use of satellite data allows us to study the variability of ionospheric plasma parameters globally without references to ground stations or receivers in different regions of the Earth. Almost ten years of in situ measurements from the Swarm satellite mission allow us to investigate the effects of changing solar activity on ionospheric variability. Here we use measurements of electron density and derived parameters that have been combined into a unique dataset called - Ionospheric Plasma IRregularities product (IPIR) [1]. The IPIR provides characteristics of plasma variability along the orbit and gives information on plasma density structures in the ionosphere in terms of their amplitudes, gradients and different spatial scales. We focused on distributions and statistics of these parameters at different latitudes in both hemispheres for different solar activity levels. We also consider quiet geomagnetic activity conditions to exclude perturbed values from a statistical study. We found that at high latitudes there is a bimodal distribution of electron density and show that the main source of such a two-peaked distribution is primarily solar illumination of the region. Our results provide information on the shape of the distribution and probability density functions of electron density and derived ionospheric parameters (such as Rate Of change of Density Index in 10 seconds, ROTI) that can be used as a baseline important for other modelling studies. Understanding the distribution of ionospheric parameters in the context of changing solar activity levels, different regions and hemispheres can have implications for developing new satellite instruments and for the accuracy of GNSS precise positioning.

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132. Noise removal to improve the Swarm-Echo magnetic field data

Associate Professor David Miles[1], Dr. Matthew Finley[2], Mr. Robert Broadfoot[1], Mr. Christopher Piker[1], Mr. Kevin Steele[1]

[1]University of Iowa, Iowa City, United States, [2]NASA Goddard Space Flight Center, Greenbelt, United States

We present improvements to the Swarm-Echo (formally Cassiope/e-POP) mission's magnetic field data product resulting from the use of modern signal processing methods to remove time-varying satellite platform magnetic noise. Swarm-Echo has a robust magnetometer payload comprising two fluxgate magnetometers mounted at different distances along a short boom. We show how evolving, spectrally complex noise sources such as overlapping reaction wheels tones can be mitigated using a technique of statistical decomposition via multichannel singular spectrum analysis, classification using gradient correlation, and then reconstruction of the target geophysical signal. These techniques are currently being used to improve the time-varying in-situ calibration of the Swarm-Echo data-product despite the non-trivial platform noise form the spacecraft. These techniques generalize to other dynamic noise sources, more than two sensors, and can be applied in certain cases to single-sensor data through the use of machine learning for classification.

133. Multipoint observations of ULF waves at LEO

Mr. Balazs Heilig[1]

[1]HUN-REN Institute of Earth Physics and Space Science, Sopron, Hungary, [2]Space Research Group, Eötvös Loránd University, Budapest, Hungary

New Swarm products have been developed for a detailed characterisation of various types of ULF waves observable at polar LEO. Using multi-point observations, the main properties of these wave types will be presented.
Dayside compressional Pc3 waves are believed to be generated in the terrestrial ion-foreshock by the backscattered solar wind protons. These waves propagate upstream in the solar wind frame, however, swept back toward the magnetosphere by the super-Alfvénic solar wind. The Doppler-shifted waves can enter the magnetosphere and propagate isotropically in the compressional mode. Approaching the Earth, the waves are reflected, however, their evanescent wave field can reach the ionosphere. Statistical properties of these waves as observed by Swarm are mostly consistent with these theoretical considerations. Although this wave type is commonly referred to as Pc3 waves, their frequency could be occasionally higher (Pc2) or lower (Pc4) depending on the actual solar wind conditions.
While compressional Pc3 waves dominate the low and middle latitudes, higher dayside latitudes are populated by shear Alfvén waves. Unlike compressional waves, shear Alfvén waves show up in the transverse components. They can be travelling waves or standing waves (field line resonances), the most typically a mixture of the two. These waves are difficult to observe directly at LEO, due to the strong Doppler shift across the narrow resonant shells traversed by polar satellites within just a few seconds. Reflected from the ionosphere, these waves partially mode convert into the compressional mode. Unlike the large-scale Pc3 waves of upstream origin, the coherence length of these waves is very short making them easily distinguishable from the first group.
Another frequently observed wave type, Pi2 waves are related to substorm onsets. Although on the ground they are observed both on the dayside and the night side, in the topside ionosphere, they were only found on the night side. Pi2 waves are the manifestations of the cavity resonance of compressional mode waves.
In the presentation, we discuss, how the multipoint constellation of Swarm has contributed to the understanding of ULF waves.

134. On the modeling and extraction of ocean tidal variability from historical geomagnetic records

Dr. Robert Tyler, Dr. David Trossman

Ocean tides generate magnetic field fluctuations that can be extracted from land, satellite, and seafloor magnetic observatory records. These tidal magnetic signals show modulations in amplitude and phase over time. A component of the observed modulations can be predicted from the temporal variations in the gravitational forcing (described with high precision by the known ephemerides of the Moon, Sun, and Earth). This component due to forcing can be recognized and removed. The remaining modulation signal is due to the changes in the ocean's tidal response, as well as potential corruption by signals due to non-oceanic sources (e.g. ionospheric tides) and sensitivities of the extracted modulations to data selection and handling.
The description and understanding of the changes over time in the ocean's tidal response are of great importance in ocean and climate studies. Discussed here is the development and application of methods for extracting and interpreting the ocean tidal modulations contained in the historical database of land geomagnetic observatories over the globe. Ancillary data for this study include tide-gauge observations and output from a high-resolution (1/30-degree) global model of the ocean tidal magnetic field to generate a predictive reference. The study's methodology involves data selection, organization of this data into a time/phase data matrix, and the extraction of principal components separating oceanic and non-oceanic components. Results show cases where the ocean tidal modulations have been successfully extracted, and other cases where the presence of other unresolved signals in the data make this a formidable challenge.

135. Modeling toroidal currents in the ionospheric electrojet regions

Dr. Patrick Alken[1], Dr. Gary Egbert[2]

[1]University Of Colorado, Boulder, United States, [2]Oregon State University, Corvallis, OR, United States

The ionospheric E-region is home to three spatially localized, intense ribbons of current known as the electrojets. The physical mechanisms driving the polar and equatorial electrojets are quite different, however the resulting currents can be well described by large-scale zonal flow in quasi-dipole coordinates. Previous methods to model the magnetic signatures of these current systems in satellite data have included line current methods, spherical elementary current systems (SECS), and spherical harmonic analysis. In this study, we introduce a novel modeling method based on principal components analysis of a large set of rotated current loops encircling the Earth in quasi-dipole coordinates. We construct a covariance function for these loops in order to build a set of 2D basis functions for each region (northern, southern, and equatorial), suitable for fitting magnetic field measurements of these current systems, both in space and on ground. The covariance function also provides a natural regularization for the fitting problem.

136. Solar System Dust Detection from Swarm Navigation Cameras – A Potential Science Add-On

Peter S. Jørgensen[1], John L. Jørgensen[1], John E. P. Connerney, Mathias Benn[1], Anja C. Andersen[3], Troelz Denver[1], Scott Bolton[4]

[1]DTU Space, Kongens Lyngby, Denmark, [2]Space Research Corporation, NASA, MD, USA, [3]University of Copenhagen, Copenhagen, Denmark, [4]Southwest Research Institute, San Antonio, Texas, USA

Dust particles in our solar system manifest themselves in several ways, on example being the Zodiacal light. While the solar system dust is believed mainly to originate from comets and asteroids, further understanding of its distribution and origin is still being explored. One set of valuable observations is the in-situ measurements of dust performed by various spacecraft.

A prime example of in-situ dust measurements is the microASC Star Tracker navigation camera, flying on the Magnetometer experiment on NASA's Juno mission to Jupiter. During Juno's 5 year cruise from Earth to Jupiter, the microASC cameras registered impacts from dust on the Juno solar panels, thus probing the local dust consecrations in the space between Earth and Jupiter. On individual occasions local increase in dust concentration was observed, which in at least one case can be linked to a specific source object.
The three Swarm satellites each carries three navigation cameras, identical to the ones flown on the Juno MAG experiment and as such offer an excellent in-flight platform for monitoring the local dust environment around Earth. The dust detection on the Swarm navigation cameras can be enabled relatively easy and would provide high time-resolution and long duration series of observations.

We summarize the existing in-situ dust measurements with focus on the Juno example and detection method and provide an outlook to the potential measurements from Swarm.

137. Implementation of the Swarm FAST Processing Pipeline

Mr. Antonio de la Fuente[1], Mr. Alessandro Maltese[2], Mr. Prabu Shanmugam[3], Ms. Livia D'Alba[4], Mr. Danilo Parente[2], Mr. Antonio Biscuso[2]

[1]European Space Agency, Frascati, Italy, [2]SERCO c/o ESA, Frascati, Italy, [3]Werum, Lueneburg, Germany, [4]RHEA c/o ESA, Frascati, Italy

The implementation of a near real-time (NRT) processing chain was discarded during the development of the Swarm Payload Data Ground Segment (PDGS) prior to launch due to technical and budgetary constraints, but only a few years into routine operations it was recognised that a low-latency processing pipeline, with optimisation of the downlink strategy, could significantly extend the exploitation of Swarm data into new scientific and engineering application domains such as Space Weather.

In 2021, it was decided to start evaluating the feasibility of a low latency L1b processor and the implementation of a parallel Swarm FAST processing pipeline. Given the limited resources, a phased approach was adopted, including a processor feasibility analysis, a 6-month processing pilot, and following scientific community endorsement at the 12th Swarm DQW in October 2022, the implementation of a new FAST robust processing pipeline.

The implementation of the new standalone FAST processing pipeline has been done using an Agile and ObsDev approach and is based on the Werum Olib framework, which will also be used in future Earth Explorer missions such as EarthCARE and Biomass. The FAST pipeline was deployed in the existing EOP-GE cloud infrastructure and systematic production started at the end of April 2023. Following scientific validation and endorsement by the scientific community, the FAST data was opened to all users in December 2023.

This poster provides details of the whole process and highlights the key elements for the success, as it was the phased and flexible approach that was chosen and the close collaboration of all the teams involved.

138. Separating magnetospheric, ionospheric and Earth-induced magnetic field contributions by joint analysis of Swarm satellite and ground observatory data

Prof. Nils Olsen[1], Prof. Chris Finlay[1], Lars Tøffner-Clausen[1]

[1]DTU Space - Technical University of Denmark, Kongens Lyngby, Denmark

Models of the large-scale magnetospheric currents are either derived from satellite data alone (e.g. MMA_F Level-2 data product) or from ground observatory data alone (resulting e.g. in the Dst and RC indices and MMA_CHAOS) or by joint analysis of both data sets (e.g. MMA_C). For all present models it is assumed that ionospheric currents are either absent or independent of geomagnetic activity (and thus can be accounted for by an ionospheric model (e.g. MIO_C) that is derived from quiet-time data).

However, it has long been noticed that the magnetospheric field as determined from ground data (e.g. Dst and RC indices) only accounts for 90% of that seen at satellite altitude, even if Earth-induced contributions are considered. This discrepancy has led to speculations about additional ionospheric currents between ground and satellite that depend on geomagnetic activity.

We investigate the existence of ionospheric currents of "ring-current geometry" (i.e. zonal currents) by simultaneous estimation of magnetospheric, ionospheric and induced currents using satellite and ground based data.

139. A climatological model of the Equatorial Electrojet derived from Swarm satellite magnetic data

Chiara de Geeter[1], Prof Nils Olsen[1], Enkelejda Qamili[2], Patrick Alken[3]

[1]DTU Space - Technical University of Denmark, Kongens Lyngby, Denmark, [2]ESA / ESRIN, Frascati, Italy, [3]University of Colorado , Boulder, USA

The Equatorial Electrojet (EEJ) is a strong horizontal electric current in the ionospheric dynamo region, located on the dayside hemisphere above the magnetic dip equator.
Latitudinal profiles of the electric sheet current density between +/- 20 degrees magnetic (QD) latitude are provided as the Swarm Level-2 EEF data product for each of the three Swarm satellites. In this study we use an extended EEF data set for Swarm Alpha and Bravo spanning nine years to derive a climatological model of the EEJ. This extended data set includes EEJ profiles not only during daytime (as in the operational EEF product) but for all Local Times.
Our model includes dependencies on UT, longitude, season, EUVAC solar flux and lunar phase and is validated with independent data from Swarm Charlie and the CSES satellite.

140. Review of the magnetic perturbation model of the Swarm Satellites

Peter Brauer[1], Ass. Prof. Lars Tøffner-Clausen[1], Prof. Gauthier Hulot[2]

[1]DTU, Lyngby, Denmark, [2]IPGP, Paris, France

The presentation will give a review of the magnetic perturbation on the magnetometers of the Swarm mission. The presentation covers the empirical model of the sun-driven disturbance vector, through investigation of the thermoelectric currents causing the disturbance, to the physical modeling of the disturbance based on the energy balance of the thermal power received from the sun on the thermal blankets.

141. Thermospheric Densities and Ionospheric Conditions During the Starlink Destruction Event

Dr. Daniel Billett[1], Kian Sartipzadeh[2], Magnus Ivarsen[1], Elisabetta Iorfida[3], Eelco Doornbos[4], Ceren Eyiguler[1], Kuldeep Pandey[1], Kathryn McWilliams[1]

[1]University Of Saskatchewan, Saskatoon, Canada, [2]University of Tromsø, [3]Aurora Technology B.V. for European Space Agency, [4]Royal Netherlands Meteorological Institute.

In February 2022, a geomagnetic storm caused the premature re-entry of 38 newly launched Starlink internet satellites. This one event cost SpaceX roughly 50 million USD in infrastructure damages alone.
Starlink satellites are deployed at a very low initial altitude of less than 350km, before boosting up to operational altitudes around 600km. This two-stage process is mainly a cost saving measure; however, the atmospheric density of the thermosphere increases exponentially with decreasing altitude. The low Starlink altitude would typically not be an issue, but during geomagnetically active conditions (even those of relatively low magnitude), enhanced electromagnetic energy from the solar wind gets deposited in the atmosphere and drives upwelling. The satellites thus experienced a large degree of drag forcing from the thermosphere, eventually resulting in their re-entry 4 days post-launch.

In this talk, we show data on the ionosphere/thermosphere conditions that led to the Starlink destruction event, including thermospheric densities from the Swarm/GRACE-FO missions, and field-aligned currents from AMPERE. We examine the latitudinal distribution of density perturbations, which persists for days following the storm. We also investigate the interhemispheric asymmetries in the density perturbations, which reveals a northern hemisphere preference.

142. Impact of Solar Flares on Upper Atmosphere: Swarm and TIMED/SABER satellites observations

Dr. Tikemani Bag[1], Prof. Yasunobu Ogawa

[1]National Institute Of Polar Research, Tokyo, Japan, Tokyo, Japan

The Nitric oxide (NO) emission at 5.3 µm wavelength represents a 'natural thermostat' by which the heat and energy are efficiently lost from the thermosphere. It is the dominating coolant above 100 km. The primary production mechanism is the temperature dependent reaction between the nitric oxide and atomic oxygen densities. Consequently, the radiative emission linearly depends on NO and Atomic
oxygen densities and non-linearly on the thermospheric temperature. We utilized the Swarm satellite observations of the thermospheric density and the NO 5.3 µm radiative emission measurements by SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) instrument onboard the NASA's TIMED (Thermosphere Ionosphere Mesosphere Energetics Dynamics) satellite along with the numerical model simulations and the EISCAT measurements to investigate the impact of solar flares on
thermospheric density and NO cooling emission during geomagnetic quiet period. Furthermore, we also quantify the spatial and temporal impacts of solar flare and their relation and cross-correlation with the thermospheric cooling emission and thermospheric density during the geomagnetic quiet periods.

143. Multi-Scale Ionospheric Poynting Fluxes Using Ground and Space-Based Observations

Dr. Daniel Billett[1], Kathryn McWilliams[1], Pasha Ponomarenko[1], Carley Martin[1], David Knudsen[2], Sarah Vines[3]

[1]University Of Saskatchewan, Saskatoon, Canada, [2]University of Calgary, Canada, [3]Johns Hopkins APL, USA.

We present high-resolution measurements from the Swarm satellites coincident with excellent F-region ionospheric coverage from SuperDARN. Convection patterns from SuperDARN, together with field-aligned-current patterns from the Active Magnetosphere and Planetary Response Experiment (AMPERE), provide information on quasi-static ionospheric dynamics traversed by Swarm. Using the SuperDARN convection electric field, we filter the Swarm electric field observations into a quasi-static component that agreed with the SuperDARN electric field. The residual electric field from Swarm is thus indicative of small- and mesoscale dynamics not captured by the convection and FAC patterns. Calculations of the Poynting flux between the different instruments show that dynamics on small- to mesoscales can be highly variable within structures like field-aligned currents. In the events shown, small- and medium-scale Poynting fluxes occasionally dominate over those from large-scale processes.

144. QUID-REGIS: Quiet Ionospheric Disturbances - REsearch based on Ground-based mesospheric and Ionospheric data with Swarm data, project started in 2024.

Dr. Jaroslav Urbar[1], Sabine Wüst[2], Šimon Mackovjak[3], Jaroslav Chum[1], Vladimír Truhlík[1], Petra Koucká Knížová[1], Lisa Küchelbacher[2], Michael Bittner[2], Carsten Schmidt[2], Patrick Hannawald[2], Ján Kubančák[3]

[1]Institute of Atmospheric Physics ASCR, Prague, Czech Republic, [2]Deutsches Zentrum für Luft- und Raumfahrt e.V., Oberpfaffenhofen, Germany, [3]Slovak Academy of Sciences, Institute of Experimental Physics , Košice, Slovakia

The day-to day variability of quiet-time ionosphere is surprisingly high even during periods of negligible solar forcing. Relatively well understood is the high-latitude variability where the solar wind is directly driving the high latitude currents, convection electric field or polar aurorae. But the current understanding does not allow to accurately model the ionospheric state during the quiet-time conditions also at mid- and low-latitudes. Surprising effects remain even at mid-latitudes, including for instance double daily maxima of ionospheric critical frequency.

SWARM measurements allow the characterization of the upper atmospheric conditions and dynamics for more than 10 years now. The analysis of SWARM data also showed that the ionosphere is sometimes disturbed even during "quiet" solar periods: the electron density and electric field, for instance, can show significant variability that currently remains unexplained.

Using SWARM data, supported by extensive ground-based measurements of both the upper mesospheric/ lower thermosphere (UMLT) and ionospheric D-, E- and F-region, we contribute to characterize the atmospheric state during these quiet periods. Thus, QUID-REGIS contributes to the understanding of disturbances in the upper atmosphere and clarifies whether these are at least in parts a result of neutral atmospheric dynamics from the lower atmosphere at mid-latitudes.

During solar quiet periods, we will analyze SWARM data to detect unexpected variability. For these periods, we will investigate measurements at lower heights for atmospheric variability. These measurements comprise airglow observations representative for the neutral atmosphere in the UMLT (80-100km), magnetic field (and other) observations representative for the ionospheric dynamo region (85-200km) as well as airglow observations from 200-300km altitude. Whenever we detect unexpected variability in SWARM data we statistically evaluate if the lower atmosphere might serve as a source region for these variabilities. Then, atmospheric waves may serve as an explanation. We will derive and analyze well-established indices of planetary wave and gravity wave dynamics in the UMLT to characterize those waves and quantitatively estimate their contribution to the observed variability in the ionosphere. We then evaluate, if the disturbances in the ionosphere during the quiet periods are causing less accurate outputs of the IRI-model, in such case we would provide the improved version of IRI model based on Swarm electron density data. We aim to deliver the typical quantities of the dynamics as a look-up table to contribute to modeling of the baseline conditions.

In summary, a better quantification of the role of UMLT wave dynamics in the occurrence of solar quiet ionospheric disturbances will be achieved along with a better representation of baseline ionospheric conditions.

145. The global observation for lightning whistlers by ZH-1 satellite.

Dr. Qiao Wang[1], Prof. Jing Yuan[3], Prof. Zeren Zhima[2], Ms Ning Mao[1]

[1]Institute Of Geophysics, China Earthquake Administration, Beijing, China, [2]National Institute of Natural Hazards, MEM, China, Beijing, China, [3]Institute of Disaster Prevention, Hebei Province, China

We use the ELF data of Search Coil Magnetometer onboard ZH-1 Satellite to recognize the global lightning whistlers. Then, the dispersion parameters were substracted from the spectrogram of the lightning whislters. These parameters will reveal the electron density and geomagnetic intensity along the propagation path of the ligthning whistler waves. We found that the lightning whistlers cover not only the lower latitude but also the higher latitude globally.

146. FBURST: A project joining Field Aligned Currents and Bursty Bulk Flows

Andrew P. Dimmock[1], Stephan Buchert[1], Yuri V. Khotyaintsev[1], Ms Vanina Lanabere[1], Octav Marghitu[2]

[1]Swedish Institute of Space Physics, Uppsala, Sweden, [2]Institute of Space Sciences, Bucharest, Romania

Magnetic reconnection in the mid-magnetotail creates short impulsive bursts of fast plasma flows (bursty bulk flows, BBFs). The sunward BBFs are responsible for most plasma transport from the magnetotail to the inner-magnetosphere, which are coupled to the high-latitude ionosphere via the formation of Field Aligned Current (FAC) systems. The FBURST project aims to advance understanding of magnetosphere-ionosphere (M-I) coupling by combining long-term ionospheric data from Swarm with magnetospheric missions such as Cluster and MMS. The location of a set of BBFs will be mapped to the ionospheric footpoint using a terrestrial field-line model such as the set of Tsyganenko models. The footpoint locations will be compared with statistical maps of FACs during the intervals when MMS and Cluster magnetotail data are available. By connecting these two datasets, we will provide a deeper insight into the behaviour of FACs in terms of the variations in current density, the distortion of their structure, and also quantification of the spatial scale. This approach will also be used to identify case studies that will be used to supplement the statistical results. FBURST project will simultaneously contribute to a better characterisation of FACs but also shed significant light on a key M-I coupling mechanism, which is not completely understood. Additionally, these results may contribute to a deeper understanding of spatially localised geomagnetic perturbations that recently have been found to be important to geomagnetically induced currents.

147. Swarm constellation orbital evolution under scientific and operational constraints

Mr. Francesco Petrucciani[2], Detlef Sieg[1], Daniel Ranuschio[2], Mikel Catania[3], Javier Sanchez[1]

[1]ESA, Darmstadt, Germany, [2]CS GmbH , Darmstadt, Germany, [3]CLC Space GmbH, Darmstadt, Germany

The Swarm mission has played a crucial role in advancing our comprehension of Earth's magnetic field. Its primary objective is to survey the geomagnetic field and its temporal changes, offering fresh insights into the Earth system by improving our understanding of the planet's interior and climate. The mission consists of three identical satellites in low Earth orbit, with two operating at a lower altitude to measure the East-West gradient of the magnetic field, and one at a higher altitude in a different local time sector.

The Swarm mission's architecture is designed to separate different sources influencing Earth's magnetic field. The three-satellites constellation features three spacecraft in two orbital planes, with two satellites (Swarm-A and Swarm-C) in a plane of 87.7º inclination and one satellite (Swarm-B) in a plane of 87.3º inclination. After the orbit acquisition phase, an initial altitude separation of around 50 km between Swarm-A/C (lower) and Swarm-B (higher) was also present, with the lower satellite starting at an altitude of 467 km. No control of the altitude has been performed until 2022, and the satellites have been left decaying freely under the effect of atmospheric drag; however active orbit maintenance is required for the lower spacecraft to control relative positions within the constellation, maintaining a separation between 4 and 10 seconds.

Over time, gravitational perturbations, atmospheric drag, and mission-specific manoeuvers have led to changes in the trajectories. While initially untouched, adjustments became necessary as the lower pair's altitude decreased and the start of the 25th solar cycle approached. Campaigns in 2019, 2021, 2022, and 2023 involved inclination changes, longitudinal separation during counter-rotating orbits phase, and orbit raises, all carefully planned to optimize scientific returns, enhance synergies, and ensure mission survival until the next solar minimum.

This paper provides a thorough analysis of orbital changes in the Swarm constellation, emphasizing the dynamic evolution of the orbital elements and its impact on mission performance. It delves into strategies executed by the Flight Dynamics Team at ESA/ESOC for adaptive orbital management, considering natural perturbations, fuel constraints, solar activity, and collision risk mitigation measures implemented during each campaign's planning phase. Furthermore, this work extends into a forward-looking perspective on the future trajectory evolution. This outlook not only anticipates potential changes but also becomes instrumental in shaping critical decisions concerning the forthcoming configuration of the constellation, ensuring the sustained success and scientific efficacy of the Swarm mission.

148. Extraction of secular variation signals of geomagnetic field and evaluation of prediction accuracy of geomagnetic field models

Doctoral Student Ning Mao[1,2], Professor Shi Chen[1,2], Associate professor Qiao Wang[1,2]

[1]Institute Of Geophysics, China Earthquake Administration, Beijing, China, [2]Beijing Baijiatuan Earth Science National Observation and Research Station, Beijing, China

The purpose of this research is to compare the secular variations of the core field calculated by IGRF and WMM with those observed by geomagnetic stations and to quantitatively evaluate the accuracy of IGRF-12 and WMM2015 in mainland China. Based on the hourly mean data of 10 geomagnetic reference stations in mainland China from 2009 to 2022, we used annual differences of monthly means and principal component analysis to eliminate the external interference field and remove the crustal magnetic field to extract the secular variation of the core field. The results are the prediction accuracy of the seven geomagnetic elements in the WMM2015 is better than that of IGRF-12, and the error will gradually increase with time. The maximum 1-year error of the total field intensity of the two models is 13 nT, and the 5-year error reaches 153.65 nT, which is difficult to meet the requirements of high-precision geomagnetic navigation. It is suggested to develop the rapid secular variation model (1 year) to improve its prediction accuracy by supplementing the multi-source magnetic survey data in China.

149. Swarm Level 2 accelerometer data processing

Dr. Sergiy Svitlov[1], Dr. Christian Siemes[2], Dr. Elisabetta Iorfida[3], M.Sc. Daniel Rotter[4]

[1]'Firma Sergiy M. Svitlov' - SMS, Hannover, Germany, [2]Delft University of Technology, Delft, The Netherlands, [3]Aurora Technology B.V. for ESA - European Space Agency (ESA), ESTEC, Noordwijk, The Netherlands, [4]'Firma Sergiy M. Svitlov' - SMS, Hannover, Germany

The Swarm mission comprises a constellation of three identical satellites carrying the same set of scientific instrumentation, including an electrostatic accelerometer intended to measure the non-gravitational forces acting on the satellite. Though the Level 1B accelerometer data are heavily distorted with various anomalies and, thus, not released to all users, sophisticated Level 2 processing algorithms allow the production of scientifically valuable along-track accelerometer data. During the 10 years of mission duration, the primary focus has been on Swarm C, whose accelerometer performs best and for which the L2 calibrated data are available for almost the whole mission timeline. In addition, 15 months of Swarm A and one month of Swarm B accelerometer data have also been released to the users. In this way, the St. Patrick's Day Storm of 2015 is covered by L2 calibrated accelerometer data of the whole constellation, while for Swarm A and Swarm C, which are flying in proximity, temporally overlapping data are available for 2014.
Because of unexpected data anomalies, Swarm Level 2 accelerometer data processing is substantially different from that of other accelerometer-carrying satellite missions. As a result of intense processing efforts, the Swarm C accelerometer continues nominal operation and regular data delivery, whereas additional supervision also enables Swarm A and Swarm B Level 2 data production. In this presentation, we provide basics on the accelerometer's operation principles, discuss possible sources and properties of data anomalies, and report details on the adopted Level 2 data processing algorithm. As a certain Level 1B accelerometer data quality degradation over time is noticeable, special attention is given to evolving processing procedures which are needed to maintain the satisfactory data quality and validity of the L2 calibrated accelerometer data, that are further converted to the thermospheric neutral mass densities.

150. Swarm Langmuir Probes and plasma data processing in 10 years

Dr. Stephan Buchert[1], Dr. Roberta Forte[2], Dr. Enkelejda Qamili[2], Dr. Lorenzo Trenchi[2], Thomas Nilsson[1], Dr. Matthias Förster[3], Anna Mizerska[4], Giuseppe Albini[5], Denise Schmidt[5], Dr. Berta Hoyos Ortega[7], Antonio De La Fuente[6], Dr. Anja Strømme[6]

[1]Swedish Institute of Space Physics, Uppsala, Sweden, [2]Serco for ESA, Frascat, Italy, [3]GFZ, Potsdam, Germany, [4]GMV, Warsaw, Poland, [5]European Space Agency, ESOC, Darmstadt, Germany, [6]European Space Agency, ESRIN, Frascati, Italy, [7]European Space Agency, ESTEC, Noordwijk, The Nehterlands

Swarm, as part of ESA's Earth Explorer missions, has been designed to measure the magnetic fields generated from Earth's core, mantle, crust, ionosphere and magnetosphere. In the past 10 years the mission greatly contributed to characterize not only the geomagnetic field and its temporal variations, but also the ionospheric plasma density, temperature, and drift as well as electric currents. Each Swarm spacecraft carries as part of the electric field instrument (EFI) two Langmuir Probes (LPs) measuring currents closing through the ionospheric plasma and the admittance. From these parameters the plasma density and temperature can be estimated. Also, the spacecraft potential is indicated which is of help when processing data of the two thermal ion imagers on each spacecraft. The LPs have been providing reliable and nearly uninterrupted data for 10 years, serving many scientific applications and studies in this field.

Plasma data processing, monitoring and distribution are the result of a synergy between ESA's Ground Segment and Data Quality team, science instruments specialists and software providers, as part of the Swarm Data Innovation and Science Cluster (DISC). This work presents an overview of the Swarm EFI LPs' instruments and processor performances during the mission lifespan, showing the main improvements introduced in the processing chain in order to enhance data quality and to meet scientific users' needs ad recommendations, such as new parameters, calibration errors, flags and new fast processing, together with further improvements foreseen in the future.

151. Space weather on Earth: how could we better preserve our technologies from space weather events?

Ms. Audrey Schillings[1,2,3], Maria Hamrin[2], Laurianne Palin[5], Hermann Opgenoorth[2], Anna Wiler[1], Marie Eldor[1], Nils Olsen[1], Liisa Juusola[4], Kirsti Kauristie[4], Gemma Bower[3], Steve Milan[3], Max Van de Kamp[4]

[1]Dtu Space, Denmark, Copenhagen N, Denmark, [2]Umeå University, Sweden, Umeå, Sweden, [3]University of Leicester, UK, Leicester, UK, [4]Finnish Meteorological Insitute, Helsinki, Finland, [5]Thales Alenia Space, Toulouse, France

Our modern society relies more and more on technologies; from GNSS (Global Navigation Satellites System) data inserted in almost every electronics to the consumption of electricity that explodes in the last decades. However, these technologies and the power lines, for example, are vulnerable to strong and quick magnetic field variations. These short-lived magnetic field variations create disturbances in the ionosphere leading to satellites signals perturbations as well as potentially induced currents on the ground. Approaching the maximum of the solar cycle in 2025, we expected an increasing number of geomagnetic storms and subsequently more of these magnetic field perturbations Space weather became more important in the last decade and its importance enlarges with our society's evolution.

Therefore, we first made a statistical study with these strong and short-lived magnetic variations during storms using superMAG data with a worldwide coverage. We confirmed two preferred locations of the spikes, one in the pre-midnight and one in the post-midnight MLT sector. We also found a spatio-temporal variation for the spikes. We then did a second statistical study for these variations during non-times storms and found the same spatio-temporal variations as well as a high number of spikes during the declining phase. Finally, we studied these variation during for one case study, the St Patrick's storm 2015, and suggested that the variations could be linked to wedgelets. While we are currently, we are studying these magnetic variations coupled with ionospheric fast flows in the sub-auroral regions also called sub-auroral polarization streams (SAPS) over the US. Radars, magnetometers and satellites data are involved and we will be happy to see how Swarm can contribute to our current studies.

152. Magnetic Anomaly Navigation with Quantum Sensors for Commercial Aircrafts

Antonia Hager[1]

[1]Airbus / NTNU Trondheim, Munich, Germany

The position of an aircraft can be determined by measuring and mapping magnetic anomalies along its flight track. This method is independent of external communication signals and can increase the redundancy of typical airborne navigation systems, a demand driven up by the increased occurrence of GPS jamming and spoofing events.

Magnetic anomaly navigation requires a precise sensor, good algorithmic compensation of the aircraft's magnetic field and georeferenced knowledge of the magnetic anomalies - from maps and models as well as in-flight recordings. Further, the impact of temporal variations and geomagnetic storms on position accuracy has to be taken into account.

To apply this technology in commercial aviation, the strong electromagnetic interference of commercial aircrafts as well as the typically high flight altitudes and air traffic routings constitute distinctive conditions. In particular, precise understanding of the system performance in all relevant flight scenarios and geographic regions must be obtained.

Here, we present an exploration of suitable quantum magnetometers and detail the specific demands of commercial aircrafts on magnetic anomaly based navigation.

153. Characterisation of hydromagnetic waves propagating over a steady, non-axisymmetric background magnetic field

Dr. Olivier Barrois[1], Pr. Julien Aubert[1]

[1]IPGP, Paris, France

Motivated by recent observations of rapid (interannual) signals in the geomagnetic data, and by advances in numerical simulations approaching the Earth's outer core conditions, we present a study on the dynamics of hydrodynamics waves evolving over a static base state.
Under the assumption of time-scales separation between the rapid waves and the slow convection, we linearise the classical magneto-hydrodynamics equations over a steady non-axisymmetric background magnetic field and a zero velocity field.
The initial perturbation is a super-rotating pulse of the inner core, which sets the amplitude and length-scales of the waves in the system. The initial pulse triggers axisymmetric, outward propagating torsional Alfvén waves, with characteristic thickness scaling with the magnetic Ekman number as Ek_M^{1/4}.
Because the background state is non-axisymmetric, the pulse also triggers non-axisymmetric, quasi-geostrophic Alfvén waves.
As these latter waves propagate outwards, they turn into quasi-geostrophic, magneto-Coriolis waves (QG-MC) as the Coriolis force supersedes inertia in the force balance.
The period of the initial wave packet is preserved across the shell but the QG-MC wave front disperses and a westward drift is observed after this transformation.
This analysis confirms the QG-MC nature of the rapid magnetic signals observed in geomagnetic field models near the equator.

154. ESA Swarm 4D Ionosphere: outline of the five contributing studies

Elisabetta Iorfida[1], Lisa Küchelbacher[2], Sabine Wüst[2], Wojciech J. Miloch[3], Heikki Vanhamäki[4], Andrew P. Dimmock[5], Christopher Finlay[6], Ilias Daras[7], Roberto Sabia[7], Anja Strømme[7], Lorenzo Trenchi[8], Matt G. G. T. Taylor[7], Diego Fernandez Prieto[7]

[1]Aurora Technology for European Space Agency (ESA) (NL), [2]DLR – German Aerospace Center (DE),[3]University of Oslo (NO), [4]University of Oulu (FI), [5]Swedish Institute of Space Physics (SE), [6]Technical University of Denmark (DK), [7]European Space Agency (ESA), [8]SERCO for European Space Agency (ESA) (IT)

In the context of the ESA Solid & Magnetic Earth Science Cluster, the "4D Ionosphere" initiative aims at advancing in the use of satellite data and technology especially from the ESA Swarm mission, in combination with additional space assets, to contribute to the development of advanced dynamic models of the Earth's ionosphere, and its interactions with the magnetosphere, the lower atmosphere, and the other components of the Earth system. The Cluster includes several projects and activities following a community approach, fostering networking, and collaborative research. This poster gives an outline of five new contributing research projects, that are jointly addressing different aspects of the ionosphere and in particular four main scientific challenges: 1) enhance the characterisation of the quiet ionosphere; 2) enhance the observation and modelling of the dynamic processes in the ionosphere: irregularities, dynamics, and predictive capabilities – space weather; 3) enhance the knowledge of the ionosphere – upper atmosphere/thermosphere coupling and 4) improve the way to observe and model the ionosphere – magnetosphere coupling. In addition, a novel activity has been also launched aiming at exploring the potential to derive ocean circulation information from geo-magnetic Swarm data. The projects, implemented by an interdisciplinary team of scientists, are: QUID-REGIS (theme: "Quiet" Ionosphere), VIP-Dynamics (theme: Dynamic Ionosphere), JOIN (theme: Ionosphere-Upper Atmosphere/Thermosphere Coupling), FBURST (theme: Ionosphere - Magnetosphere Coupling), SfOD (theme: Swarm for Ocean).

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