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

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In the context of the ESA's Solid & Magnetic Earth Science Cluster, the 4D Ionosphere initiative aims to advance the use of satellite data, particularly from the Swarm mission, along with additional space assets to contribute to the development of advanced dynamic models of 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 that follow a community approach, fostering networking and collaborative research.

This poster outlines five new contributing research projects, kicked-off in January and February 2024. They jointly address different aspects of the ionosphere and, in particular, four main scientific challenges: 1) enhance the characterisation of the quiet ionosphere (**QUID-REGIS**); 2) enhance the observation and modelling of dynamic processes in the ionosphere such as irregularities, dynamics, and predictive capabilities – space weather (**VIP-Dynamic**); 3) enhance knowledge of the ionosphere – upper atmosphere/thermosphere coupling (**JOIN**); 4) improve the way to observe and model the ionosphere – magnetosphere coupling (**FBURST**). In addition, a novel activity has been launched to explore the potential of deriving ocean circulation information from geo-magnetic Swarm data (**SfOD**).

QUID-REGIS

Quiet Ionospheric Disturbances - Research based on Ground-based mesospheric and Ionospheric data with Swarm data

Motivation:
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. However, the current understanding does not allow to accurately model the ionospheric state during the quiet-time conditions also at mid- and low-latitudes.

Objectives:
The project contributes to a better understanding of the variability in the Swarm data during solar quiet periods by considering atmospheric dynamics from below. The team aims to deliver a quantitative estimation of the lower atmospheric forcing as a potential source of ionospheric variability during solar quiet periods over a decade, taking advantage of measurements from a broad network of ground-based instruments from 80 km to 200 km to identify similarities in atmospheric disturbances propagating from the lower atmosphere (UMLT) up to the ionosphere. The International Reference Ionosphere Model (IRI) is evaluated considering the role of atmospheric dynamics in ionospheric disturbances and improve the IRI model for a better general baseline representation of Swarm.

The work to be performed is subdivided into three main steps:
1. Collection of data and definition of solar quiet ionosphere
2. Statistical analysis and case studies during solar quiet periods
3. Evaluation of the IRI model for a better general baseline for Swarm

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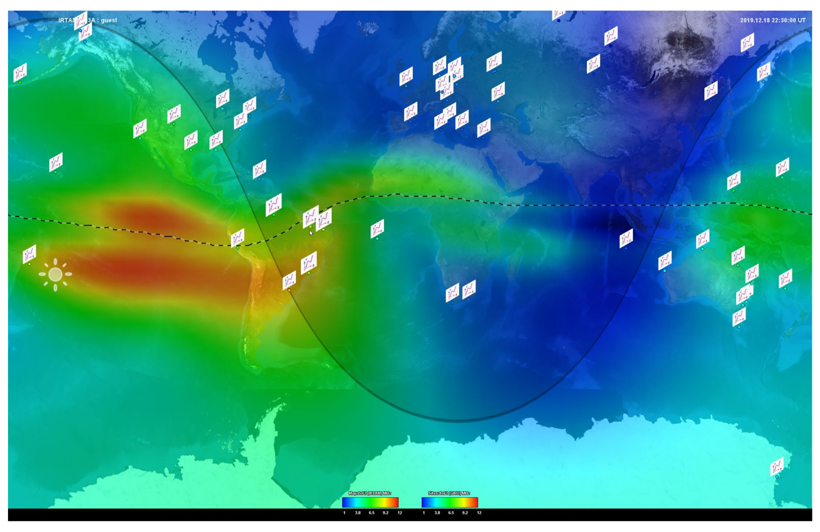

Figure 1.1 An example of the IRI real time assimilative mapping in the retrospective mode (IRTAM, time of validity on December 18, 2019, and 22:30h UT) and available digisonde data from the GIRO database used for this case. The global distribution of foF2, circles and graph icons representing digisonde stations are shown.

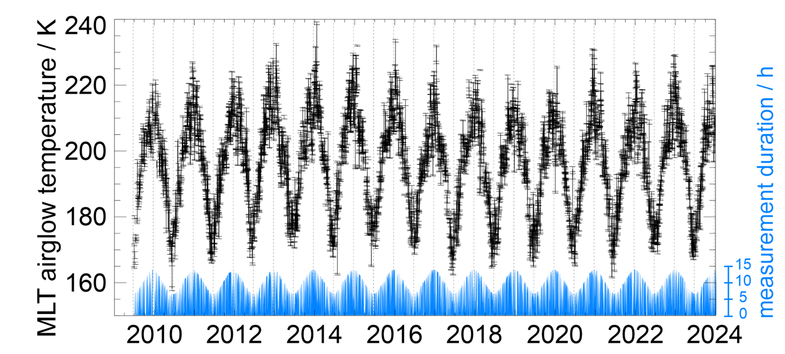

Figure 1.2 Nightly mean values of OH airglow temperature observations (MLT) from UFS station (47.42°N, 10.98°E) spanning 1.7.2009 – 1.1.2024. Dashed lines mark summer and winter solstices; blue indicates effective observation time. Notable is the annual cycle with warm winters and cool summers and the solar cycle effect of approximately +6K/100sfu (see details in Schmidt et al. 2023; https://doi.org/10.5194/amt-16-4331-2023). The original temporal resolution with up to 10s allows the study of rather short-term variability.

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SWARM VIP-Dynamic

Swarm Space Weather: Variability, Irregularities, and Predictive capabilities for the Dynamic ionosphere

Objectives:
- Develop a suite of Swarm-VIP-Dynamic models for capturing the topside ionosphere structuring and dynamics at various scales, including small scales.
- Predict key-quantities and demonstrate the operation of such models to operate in real-time environment.
- Use adapted generalised linear modelling / probabilistic models / and machine learning methods
- Trial number of explanatory variables in the context of heliophysical proxies.
- Model densities, density gradients, amplitude of density variations.
- Improve previous models.

Tasks and foreseen outcomes
- Exploit the Swarm satellite data to develop a suite of Swarm-VIP-Dynamic models.
- 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.
- Explore and demonstrate the Swarm-VIP-Dynamic model's predictive capabilities in the context of space weather and space weather effects, testing the feasibility of the models to be used in a real-time environment.
- Such a demonstration of the spacecraft-based models and forecasts will be of importance for paving the way for further development within the sector. Accurate and advanced space weather services are a necessity in the years to come.

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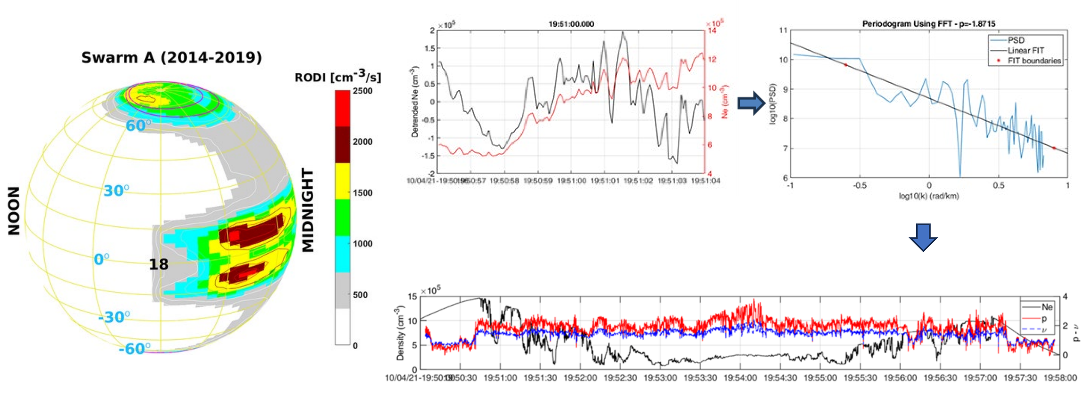

Figure 2.1 Swarm VIP Dynamic will build models based on Swarm datasets, including the Swarm IPIR dataset for characterising ionospheric plasma irregularities and 16Hz plasma density data. (left): Statistics of RODI showing largest occurrence of plasma irregularities in the post-sunset equatorial sector and in the polar regions (Jin et al. 2020), (right) 1D spectral slope p of the power spectrum of the plasma density irregularities at 16Hz, evaluated by linear fitting on the log-log power spectral density (PSD) of the plasma density data on the same time window of RODI (Imam et al. 2023).

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JOIN

Joule heating effects on ionosphere-thermosphere coupling and neutral density

Objectives:
This project aims to study the auroral Joule heating and its consequences on the ionosphere-thermosphere (IT) system at high latitudes. The main objectives are:
1. Determine the global statistical distribution and variability of the high-latitude Joule heating during geomagnetic storms.
2. Correlate the time-series Joule heating with observed large-scale atmospheric density variations at low Earth orbits (LEO), see Figure 3.1.
3. Estimate variations in the atmospheric scale height by directly comparing density measurements from two different altitudes during co-planarity periods between various LEO satellites at polar orbits, see Figure 3.2.
4. Perform event studies of meso-scale Joule heating and density variations at auroral regions during conjunctions between Swarm satellites and incoherent scatter radars.

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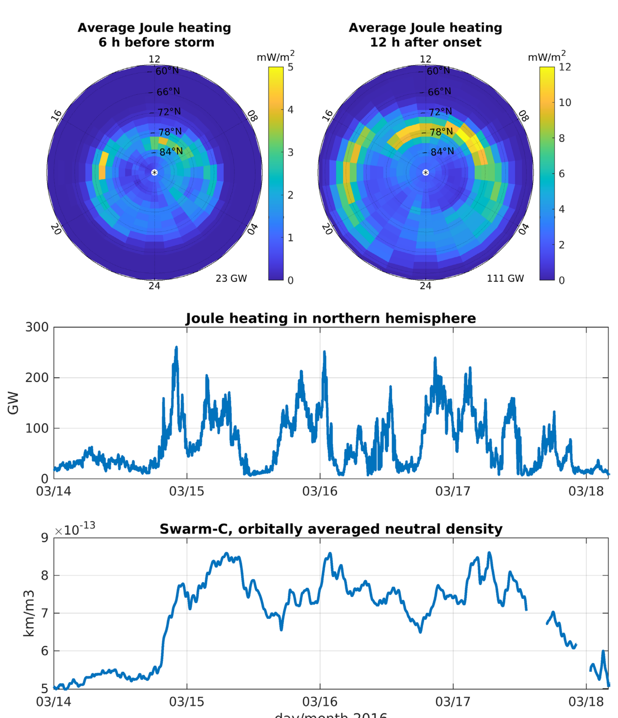

Figure 3.1. Joule heating in the northern hemisphere and orbitally averaged neutral density during a moderate (SYM-H -69 nT) geomagnetic storm that started at 19 UT on 14 March 2016. Top panels show average Joule heating patterns before the storm onset (6-hour average) and after the onset (12-hour average) calculated from SuperMAG, SuperDARN and AMPERE data. Middle panel shows time series of the hemispherically averaged Joule heating, while the bottom panel shows orbitally averaged neutral density from Swarm-C (altitude ~450 km).

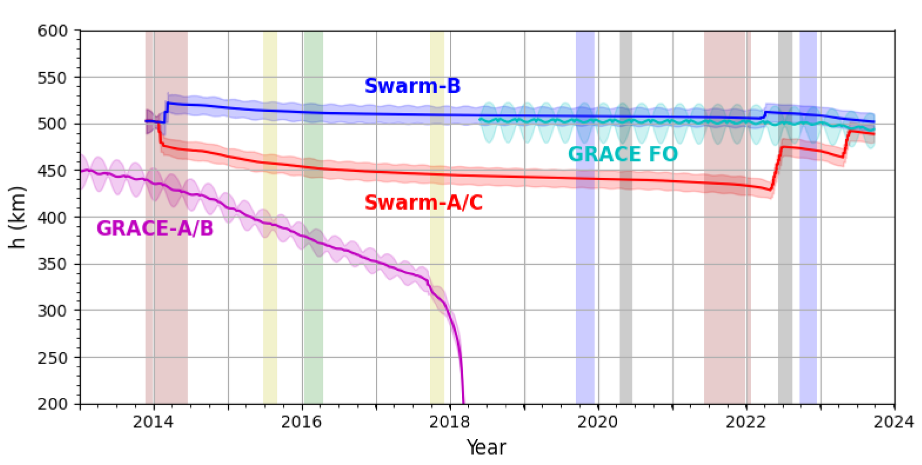

Figure 3.2. Altitudes of selected ESA satellites and co-planarity periods. Thick lines show the mean altitude and shadings the minimum and maximum altitudes per orbit. The vertical shadings mark the co-planar periods with a less than 1 h local time separation at the equator between different satellite pairs (Swarm-A and -B in red; Swarm-A and GRACE-A/B in yellow; Swarm-A and GRACE-FO in gray; Swarm-B and GRACE-A/B in green; Swarm-B and GRACE-FO in blue).

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F-BURST

Mapping of Field -aligned currents in the ionosphere and BURSTY bulk flows in the magnetotail

Key Science Questions:
- SQ1: How do BBFs influence FAC behaviour?
- SQ2: How do BBFs modulate FAC planarity and spatial scales?

This project explores ionosphere-magnetosphere coupling using data from ESA missions (Cluster, Swarm) and non-ESA missions (e.g., MMS). It focusses on Bursty Bulk Flow (BBF) events, mapping their magnetospheric position to footprints in the ionosphere. Using this, the team analyses the relationship between BBFs and Field-Aligned Currents (FACs). The BBF database and footprint points will be publicly available, facilitating detailed case studies through conjunction analysis with other missions. The project runs for 2-years and is a collaboration between the Swedish Institute of Space Physics in Uppsala, and the Institute of Space Sciences in Bucharest, Romania.

Institutet för Rymdfysik – IRF Swedish Institute of Space Physics · ISS

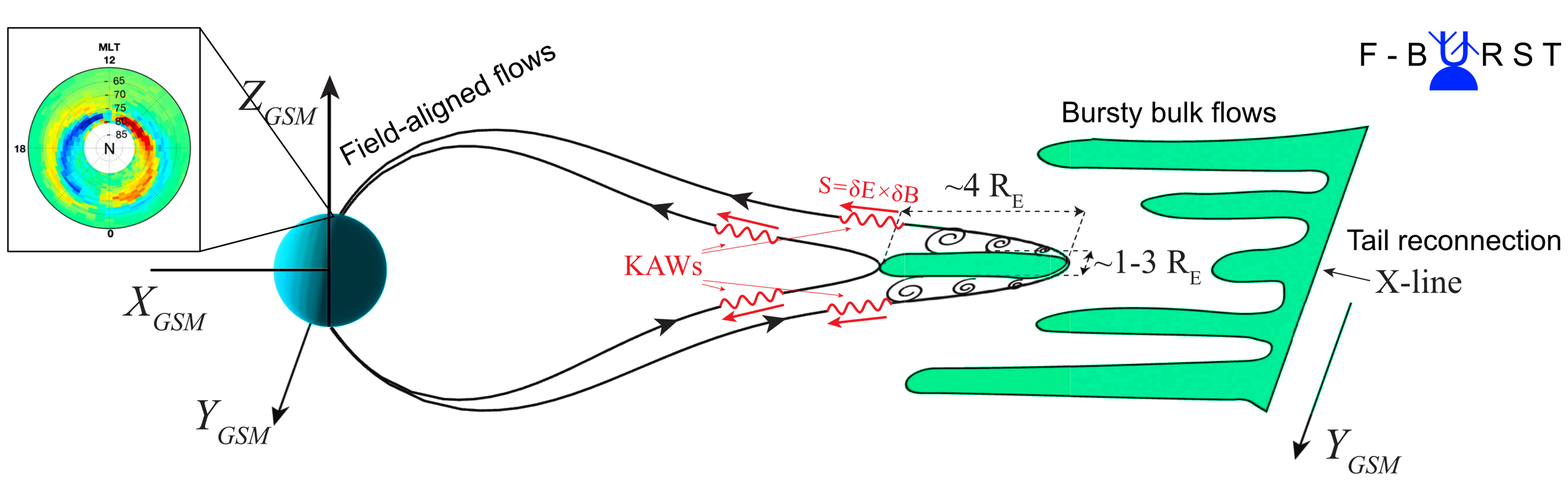

Figure 4.1 Adapted from Richard PhD thesis (2024) and Workayehu+ (2019).

F-BURST

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SfOD

Swarm for Ocean Dynamics Project

Satellite magnetic field observations have the potential to provide information on dynamics, heat content and salinity throughout the ocean. With ten years of high-quality observations available from the Swarm satellite trio, there are now new possibilities for extracting this signal of interest. This project aims to retrieve the Ocean-Induced Magnetic Field (OIMF) signal, going beyond previously identified tidal signals, and to interpret this with the help of advanced numerical simulations, by:

- Dedicated processing of Swarm magnetic data with corrections for known magnetospheric and ionospheric signals
- High resolution global modelling of the time-dependent internal field at Earth's surface using this processed data
- Spatio-temporal filtering to isolate the time-varying OIMF signal
- Analysis of high-resolution numerical simulations based on 4D oceanic flows and conductivities.

DTU · Faculty of Mathematics and Physics, Charles University

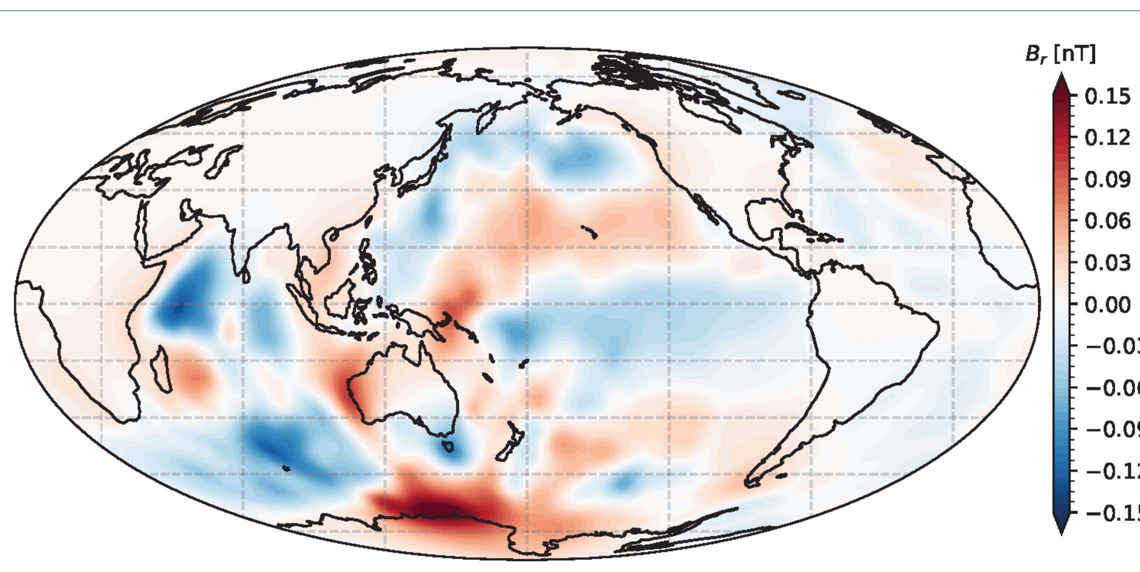

Figure 5.1 Radial component of simulated ocean-induced magnetic field (OIMF) at satellite altitude 450km, in 2016.5. The signal has been filtered to highlight variations in a period band around 1 year. Credit: DTU/CUP

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SWARM 10 YEAR ANNIVERSARY SCIENCE CONFERENCE
08–12 April 2024 | Copenhagen, Denmark