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

W. Miloch¹, Y. Jin¹, D. Kotova¹, A. Wood², G. Dorrian², L. Alfonsi³, L. Spogli³, R. Imam³, E. Doornbos⁴, K. van Dam⁴, M. Hoque⁵, J. Urbar⁶

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
Swarm and plasma variability

Swarm mission can successfully address the ionospheric variability at larger scales in relation to geophysical proxies (Wood et al., 2024, Spogli et al., 2024).

Example model: Polar model of $|\text{GradNe@100km}|$

$$|\text{GradNe@100}| = \left( \exp \left( -1.9 + 5.3 \times 10^{-3} \cdot F_{107,81} + 9.1 \times 10^{-3} \cdot |\text{MLAT}| + (\ldots) + 1.3 \times 10^{-3} \cdot \text{SYM}_D \right) \right)^3$$

- $F_{107,81}$: 81 day average of the F10.7cm solar flux, centred on the day to be updated
- $|\text{MLAT}|$: Absolute value of magnetic latitude (in degrees)
- $\text{SYM}_D$: The longitudinally symmetric disturbances to the terrestrial magnetic field perpendicular to the dipole axis

Models created for Ne, $|\text{Grad}_\text{Ne@100km}|$, $|\text{Grad}_\text{Ne@50km}|$, $|\text{Grad}_\text{Ne@20km}|$, and the IPIR index in the polar, auroral, mid-latitude and equatorial regions.
Swarm VIP Dynamic – main goals

• Develop a suite of Swarm-VIP-Dynamic models for capturing the topside ionosphere structuring and dynamics at various scales, including small scales.

• Use datasets from other satellites and from ground-based instruments for validation and to explore their added value.

• Explore and demonstrate the Swarm-VIP-Dynamic model’s predictive capabilities in the context of space weather and space weather effects / near-real time.
**Tasks:**
WP2.1 Swarm IPIR dataset

Spacecraft: Swarm C  
Period: 17 April 2024 - KoM

+ Thermospheric density from ACCxCAL2 from Swarm C

Available in the old models

RODI Available in the new model
When creating these models, the following explanatory variables will be considered:

- **Solar Activity**: F10.7 cm solar radio flux (observed) & the sunspot number R.
- **Solar Wind**: Bulk speed, density, pressure, the x-, y-, z- components of the Interplanetary Magnetic Field (IMF), the clock angle, the Interplanetary Electric Field (IEF), the Newell solar wind coupling function (Newell, 2007) and the Akasofu solar wind coupling function (Akasofu, 1996), calculated over a two-hour interval leading up to the time of interest. The clock angle, $\theta_c$, is given by $\arctan\left(\frac{B_y}{B_z}\right)$ where $B_y$ and $B_z$ are the y- and z-components of the IMF respectively.
- **Newell’s solar wind coupling function** is given by $v^{4/3} \cdot B_T^{2/3} \cdot \sin^{8/3} \left(\frac{\theta_c}{2}\right)$ where $v$ is the solar wind velocity and $B_T$ is the magnitude of the IMF. Akasofu’s solar wind coupling function is given by $v B_T^2 \sin^4 \left(\frac{\theta_c}{2}\right)$
- **Location**: Functions based on the geographic latitude (LAT), geographic longitude (LON), magnetic latitude (MLAT), magnetic longitude (MLON) local solar time and magnetic local time (MLT).
- **Complementary observations from Swarm**: The thermospheric density inferred from the Swarm level 2 data product ACCxCAL2.
- **Miscellaneous**: Solar zenith angle (SZA), a function based on the solar time (ST) to represent the diurnal variation and functions based on day of year (DOY) to represent the seasonal variation.
Tasks:
WP2.4 Dataset from other missions

Assess the availability of data products from other missions (e.g.):
- COSMIC-2
- Formosat-5
- Swarm E/ePOP
- NORSAT
- BRIK-II
- International Space Station

Use: development, validation/cross-validation and performance assessment

The capability of providing information about small-scale ionospheric irregularities will also be consolidated.
Tasks:
WP2.5 Database for ground GNSS

Scintillation indices and ROT by Ionospheric Scintillation Monitor Receivers (ISMRs) owned by UiO, INGV and DLR and those constituting the ESA’ ERICA and IBISCO projects databases.

TEC N-S gradients at various spatial scales will be collected by using data from freely available local networks of GNSS receivers (e.g.):

RING network of INGV
RBMC-IBGE network
NMA network

Used mainly for performance assessment purposes

Spogli et al. (2024), https://doi.org/10.1051/swsc/2024003

Swarm VIP Dynamic – main datasets
**Linear Model**

\[ E(y) = \beta_0 + \beta_1 \cdot x_1 \]

**Multivariate Linear Model**

\[ E(y) = \beta_0 + \beta_1 \cdot x_1 + \cdots + \beta_n \cdot x_n \]

**Generalised Linear Model**

\[ g(E(y)) = \beta_0 + \beta_1 \cdot x_1 + \cdots + \beta_n \cdot x_n \]

The dependent variable does not have to follow a normal distribution

**Equation may have a different form**

\[ E(y) \quad is \ the \ expected \ value \ of \ the \ dependent \ variable \ y \]

\[ x_1 \cdots x_n \quad are \ the \ independent, \ or \ explanatory, \ variables \]

\[ \beta_1 \cdots \beta_n \quad are \ the \ parameter \ estimates \ for \ the \ model \]

**Dependent variable**  
\( y \quad To \ be \ predicted \)  
**Ionospheric variability**

**Explanatory variables**  
\( x_1 \cdots x_n \quad May \ influence \ y \)  
**Helio-geophysical proxies**
Swarm VIP Dynamic – approach

• Thermospheric contribution
• Trial longitude as an explanatory variable in the models
• Vary the lags for proxies for the solar wind
• Interhemispheric differences
• Probabilistic models
• Different machine learning methods

Parameter space is huge, so we apply a two-stage process:

Preliminary models and final models
Preliminary Models: Dependent variables

Final choice to be made in May 2024, but we anticipate:

**Whole mission lifetime**
- $|\text{Grad}_\text{Ne}@100\text{km}|$, $|\text{Grad}_\text{Ne}@50\text{km}|$ and $|\text{Grad}_\text{Ne}@20\text{km}|$ which act as proxies for the variability of ionospheric plasma at spatial scales of 100 km, 50 km and 20 km respectively. These are available within the Swarm level 2 data product IPDxIRR_2F (Jin et al., 2022)
- ROD, RODI10s and RODI20s which are the rate of change of density, the standard deviation of ROD over 10 seconds and the standard deviation of ROD over 20 seconds respectively.
- delta_Ne10s, delta_Ne20s and delta_Ne40s which are proxies for the electron density fluctuations on scales of less than 75 km, 150 km and 300 km respectively.
- The plasma density will also be modelled.

**Subset of mission lifetime**

RODI and other parameters based on 16 Hz faceplate measurements

A subset of these selected in October 2024 for final models
• Dependent variables taken from Swarm C
• Use data from 17\textsuperscript{th} April 2014 - date
• Check that distributions and link functions in the earlier models are still appropriate

**Swarm-VIP-Dynamic**

• Add the heliogeophysical proxy which best explains the trends to the model
  (the proxy with the highest correlation to the dependent variable)

• Add the heliogeophysical proxy which best explains the remaining trends
  (the next highest correlation to the dependent variable, excluding any proxy which is correlated with any term already in the model by more than |0.25|)

• Continue until no more proxies make a significant difference
  (no more are correlations to the dependent variable are statistically significant at the 5% level)
Swarm VIP Dynamic - timeline

February 2024 – February 2026

Initial models: early 2025

Space weather applications and assessment: early 2025

First final models ready in summer 2025!