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

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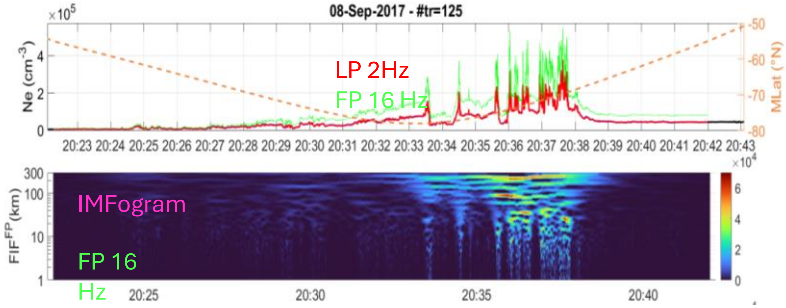
Swarm 10 Year Anniversary & Science Conference 2024

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 |GradNe@100km|

$$|GradNe@100| = \left(\exp\left(\begin{matrix}-1.9 + 5.3x10^{-3} \cdot F107_{81} + 9.1x10^{-3} \cdot |MLAT| + \\ + (\ldots) + 1.3x10^{-3} \cdot SYM\_D\end{matrix}\right)\right)^3$$

$F107_{81}$	81 day average of the F10.7cm solar flux, centred on the day to be updated
|MLAT|	Absolute value of magnetic latitude (in degrees)
SYM_D	The longitudinally symmetric disturbances to the terrestrial magnetic field perpendicular to the dipole axis

Models created for Ne, |Grad_Ne@100km|, |Grad_Ne@50km|, |Grad_Ne@20km|, and the IPIR index in the polar, auroral, mid-latitude and equatorial regions.

SWARM VIP
SWARM SPACE WEATHER
VARIABILITY OF IONOSPHERIC PLASMA

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.

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Swarm VIP Dynamic – main datasets

Tasks:
WP2.1 Swarm IPIR dataset

Available in the old models

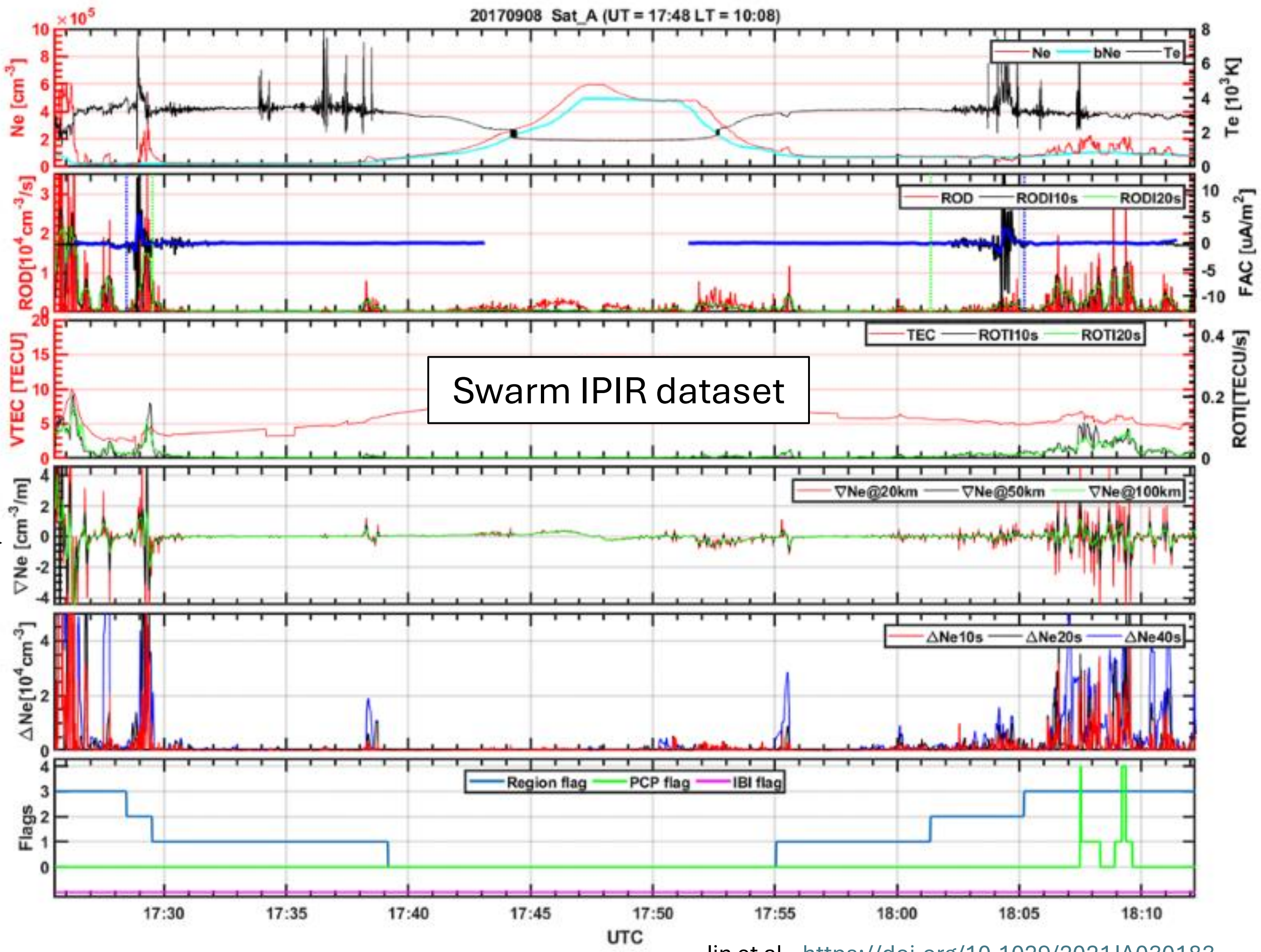
RODI
Available in the new model

Available in the old models

Spacecraft: Swarm C
Period: 17 April 2024 - KoM

+

Thermospheric density from ACCxCAL2 from Swarm C



Jin et al., https://doi.org/10.1029/2021JA030183

Swarm VIP Dynamic – main datasets

Tasks:
WP2.3 Ancillary dataset

When creating these models, the following explanatory variables will be considered:

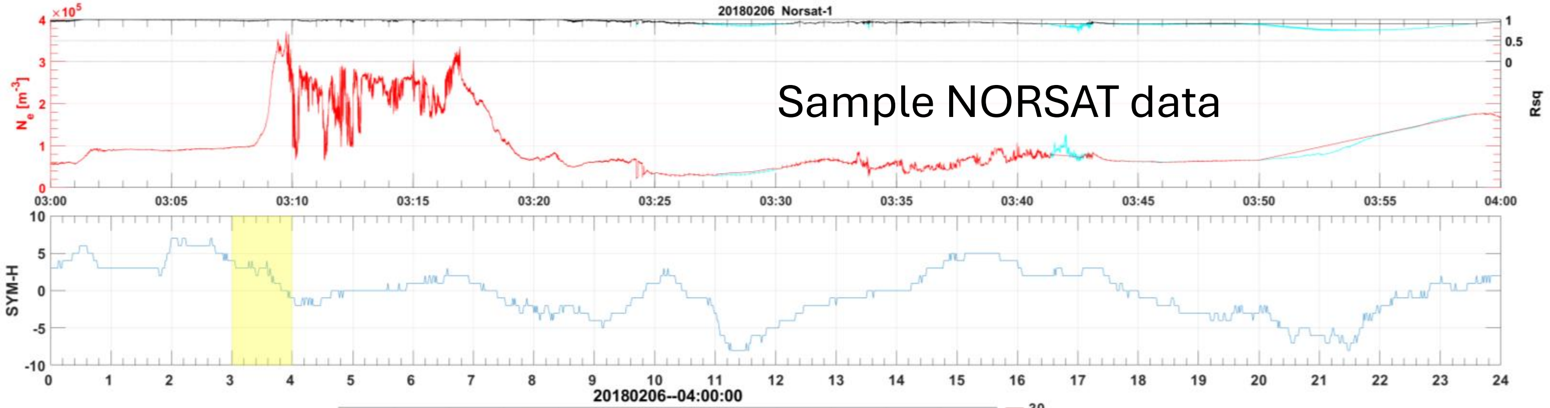
- Solar Activity: F10.7cm solar radio flux (observed) & the sunspot number R.
- Solar Wind: Bulk speed, density, pressure, the x-, y-, z- components of the Interplanetary Magnetic Field (IMF), the clock angle, the Interplanetary Electric Field (IEF), the Newell solar wind coupling function (Newell, 2007) 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, θ_c, is given by $arctan\frac{|B_y|}{B_z}$ 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 $vB_T{}^2 sin^4\left(\frac{\theta_C}{2}\right)$
- Geomagnetic activity: The aa, AE, am, AL, Ap, ASAY-D, ASY-H, AU, Dst, Kp, Polar Cap (North) index (PCN), SYM-D and SYM-H indices.
- 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.

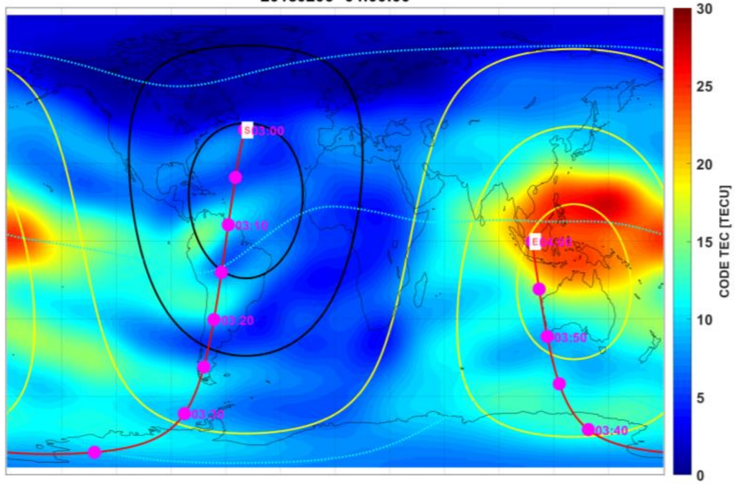
Mostly solar wind and other helio-geophysical indices to drive the model

Swarm VIP Dynamic – main datasets

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.

Swarm VIP Dynamic – main datasets

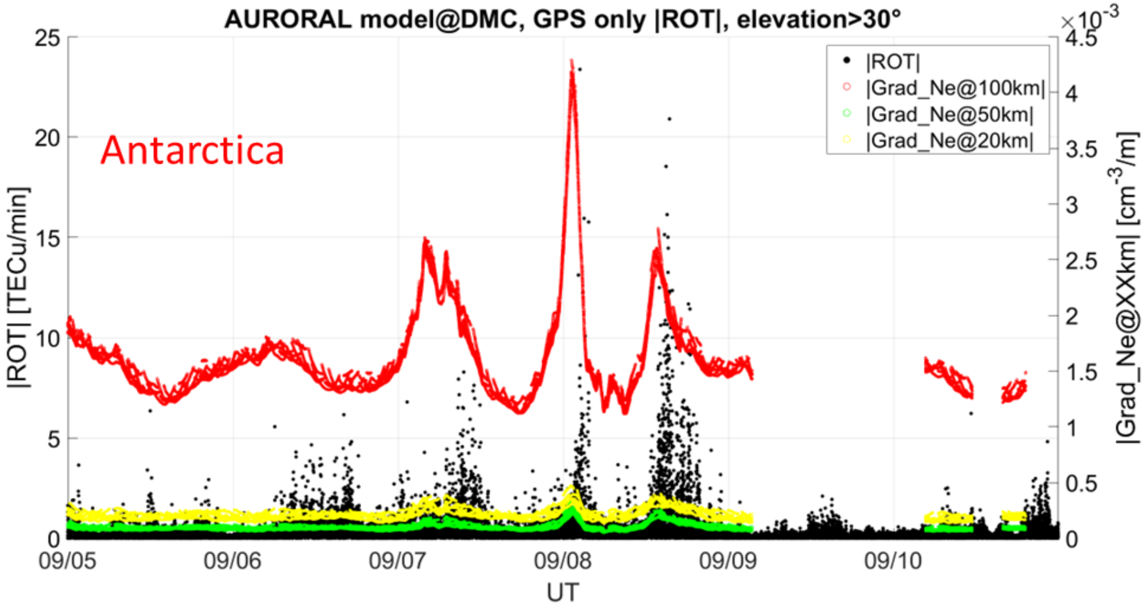
Tasks:
WP2.5 Database for ground GNSS

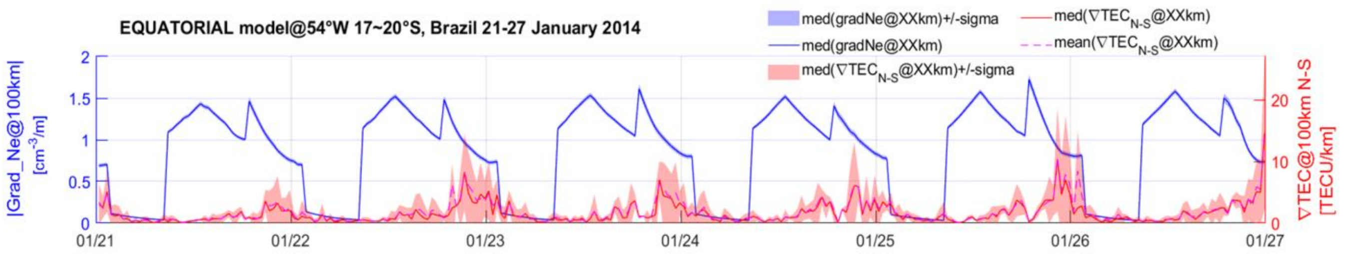
Scintillation indices and ROT by Ionospheric Scintillation Monitor Receivers (ISMRs) owned by UiO, INGV and DLR and those constituting the ESA' ERICA and IBISCO projects databases.

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 perfomance assement purposes





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

Swarm VIP Dynamic – approach

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

$E(y)$ *is the expected value of the dependent variable* y

$x_1 \cdots x_n$ *are the independent, or explanatory, variables*

$\beta_1 \cdots \beta_n$ *are the parameter estimates for the model*

Dependent variable	y	*To be predicted*	*Ionospheric variability*
Explanatory variables	$x_1 \cdots x_n$	*May influence* y	*Helio-geophysical proxies*

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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

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Swarm VIP Dynamic – foreseen outcomes

Preliminary Models: Dependent variables

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

Whole mission lifetime

- |Grad_Ne@100km|, |Grad_Ne@50km| and |Grad_Ne@20km| 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

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Swarm VIP Dynamic – foreseen outcomes

- Dependent variables taken from Swarm C
- Use data from 17th 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)

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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!

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