SWARM VIP
SWARM SPACE WEATHER
VARIABILITY OF IONOSPHERIC PLASMA

Swarm – VIP: Variability of Ionospheric Plasma studied and modelled based on data from the Swarm satellites

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SERENE Space Environment & Radio Engineering

esa European Space Agency

Swarm + Ionosphere
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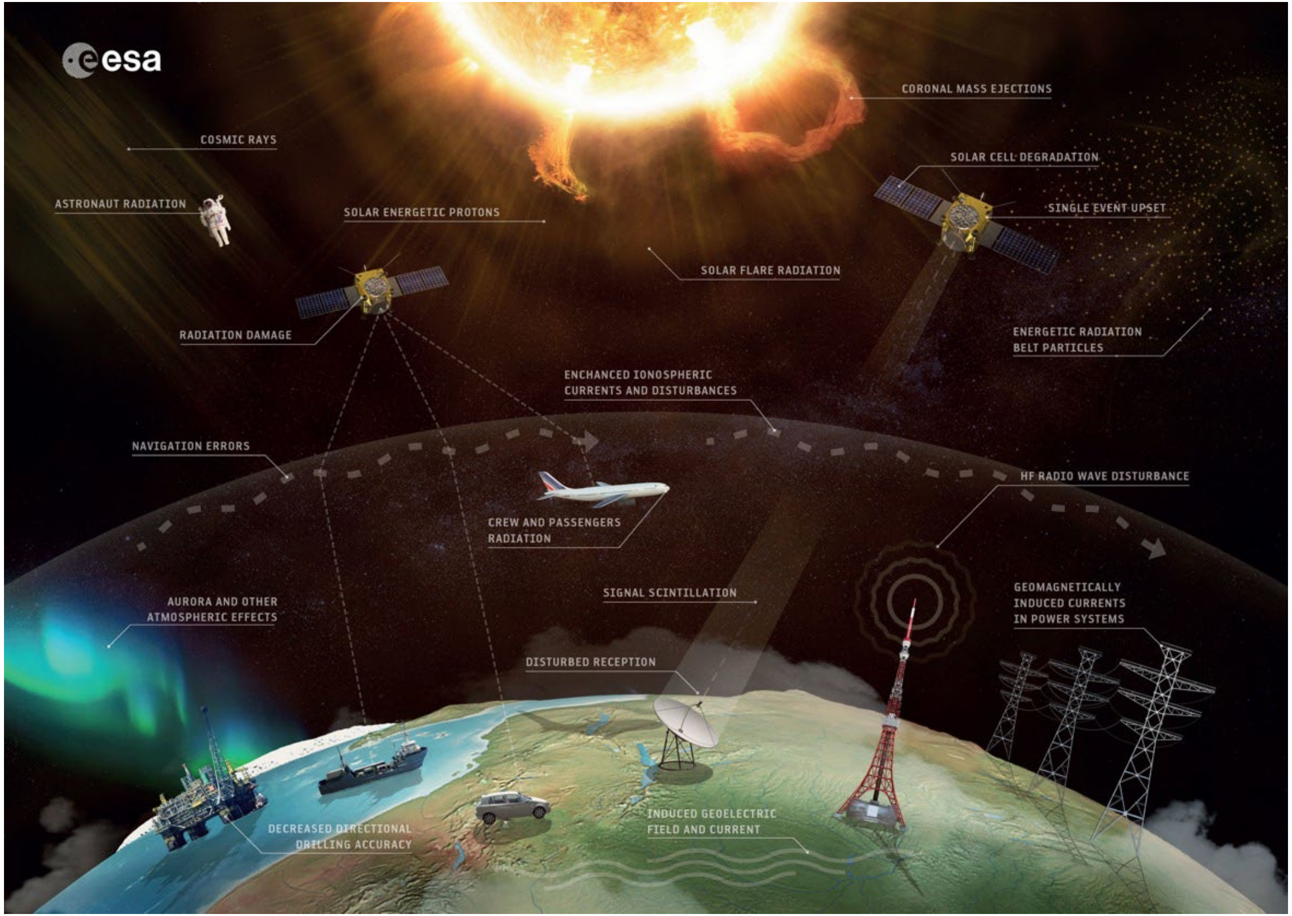

Context:

Space Weather

Ionospheric variability and irregularities are a part of the space weather system

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Swarm-VIP: Variability of Ionospheric Plasma

We address the following science challenges within the 4DIonosphere:

- Understanding climate/weather in the ionosphere (Quiescent Space Climate/Weather).
- Understanding extreme weather in the ionosphere (Extreme Weather in Space).
- Physics of ionospheric perturbations and small-scale variability.

Based on Swarm L1 and L2 datasets, and with supporting external relevant datasets, we established a new Swarm-based semi-empiric ionospheric model.

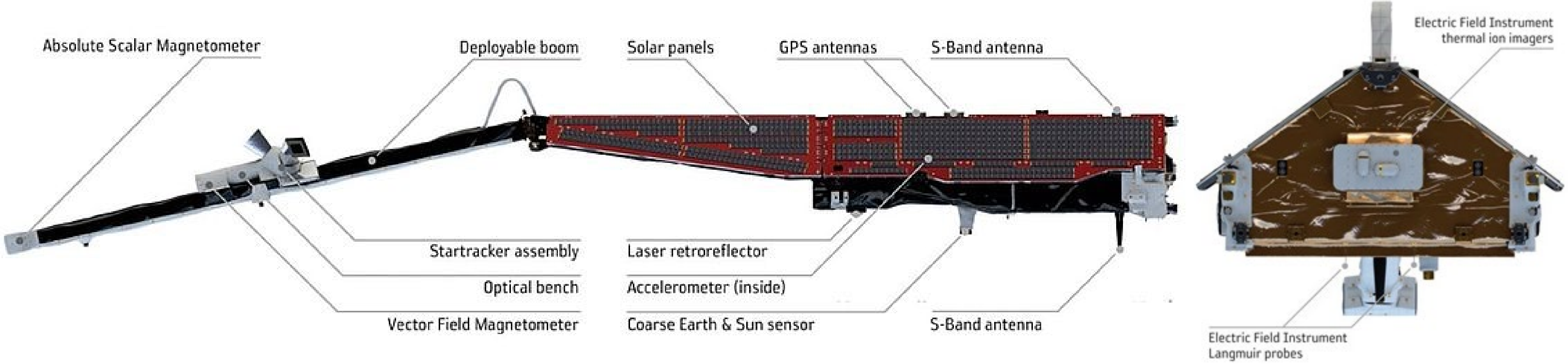

Image credit: ESA

All three Swarm satellites are equipped with a set of six instruments: Absolute Scalar Magnetometer (ASM), Vector Field Magnetometer (VFM), Star Tracker (STR), Electric Field Instrument (EFI), GPS Receiver (GPSR), Accelerometer (ACC).

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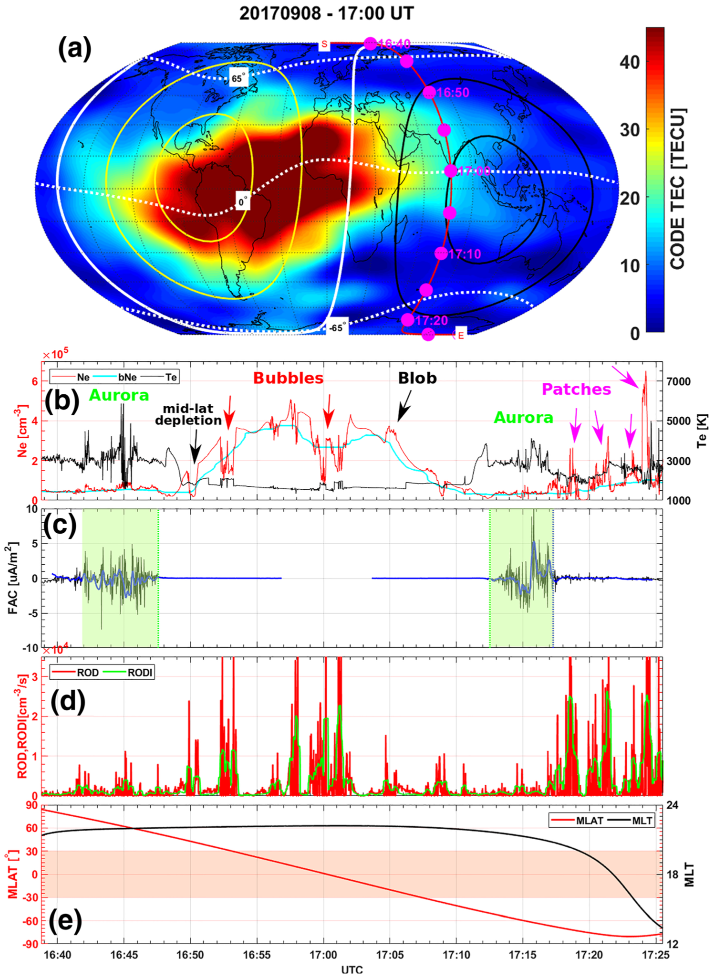
Swarm-VIP: Variability of Ionospheric Plasma



Example of Swarm - IPIR data product

Jin et al. JGR 2020

Swarm can help addressing the outstanding questions:

- What is the characteristics of the space weather/climate in the ionosphere and the extreme events over time?
- What is the physics behind ionospheric perturbations?
- What is the spatiotemporal variability of the Earth ionosphere in relation to external drivers both during quiescent and extreme conditions?

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Fast Iterative Filtering in a nutshell

Fast Iterative Filtering (FIF) algorithm

is a decomposition method that split a nonstationary signal s into simple oscillatory components, a.k.a. IMCs

Thm – Fast Iterative Filtering (FIF) convergence – C., Zhou - '21

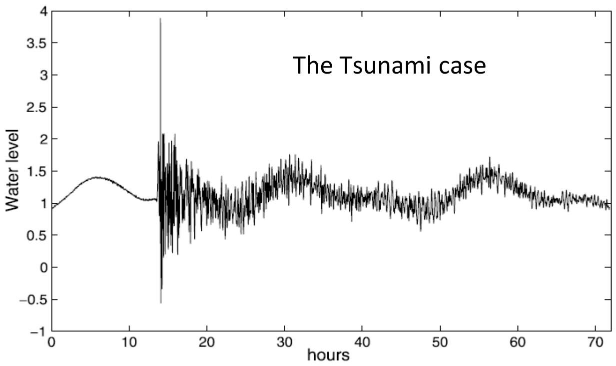
Given $s \in \mathbb{R}^n$, a filter w and periodical extension at the boundaries, Then

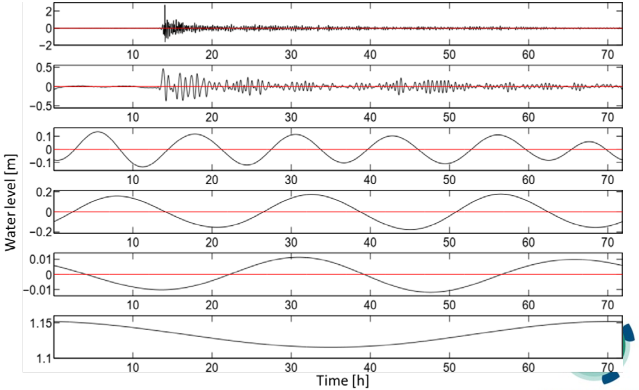
$$\mathrm{IMC}_1 = U(I-D)^{N_0} U^T s = \mathrm{IDFT}\left(\left(I - \mathrm{diag}\left(\mathrm{DFT}(w)\right)\right)^{N_0} \mathrm{DFT}(s)\right)$$

Fast calculations

The **FIF algorithm** is convergent and stable, and, on average, roughly **100 times faster than IF and EMD-based methods**.

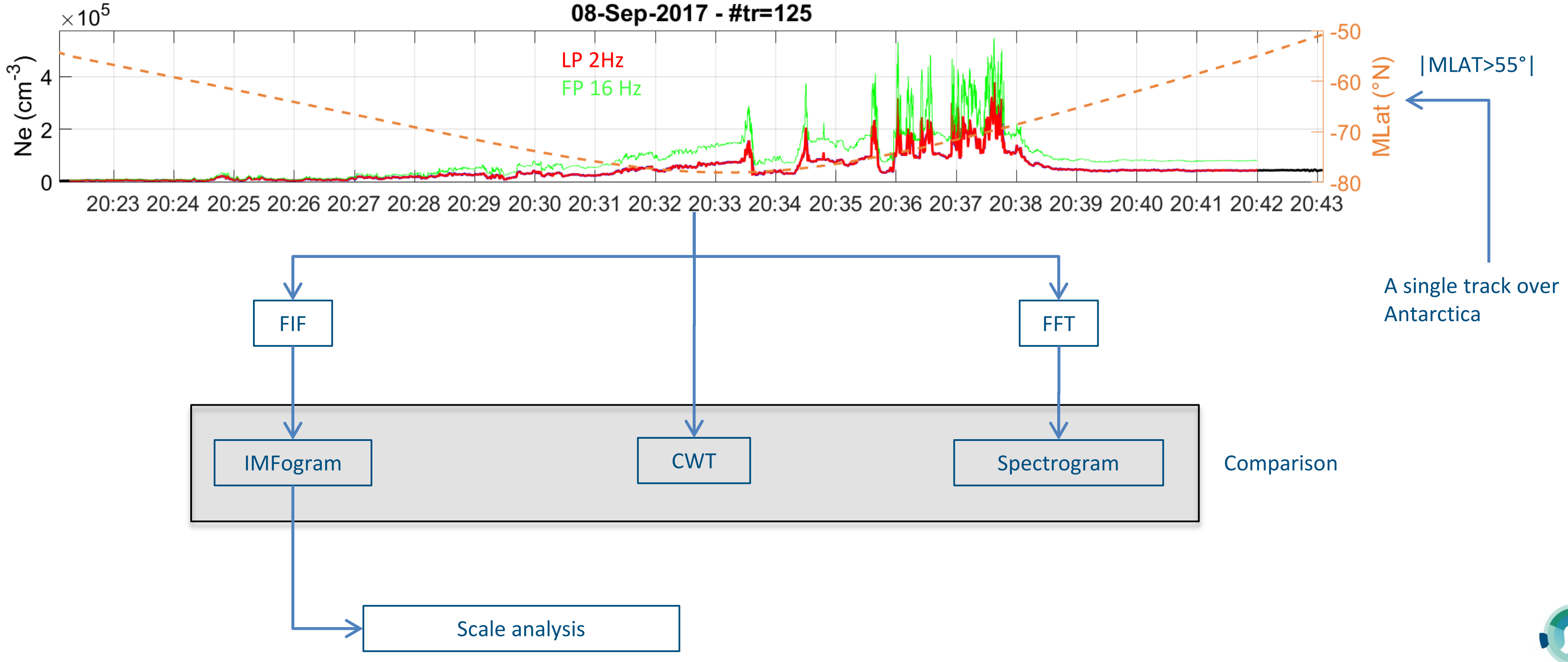
$$s = \sum_{i=1}^{N_{IMC}} IMC_i(v) + res$$



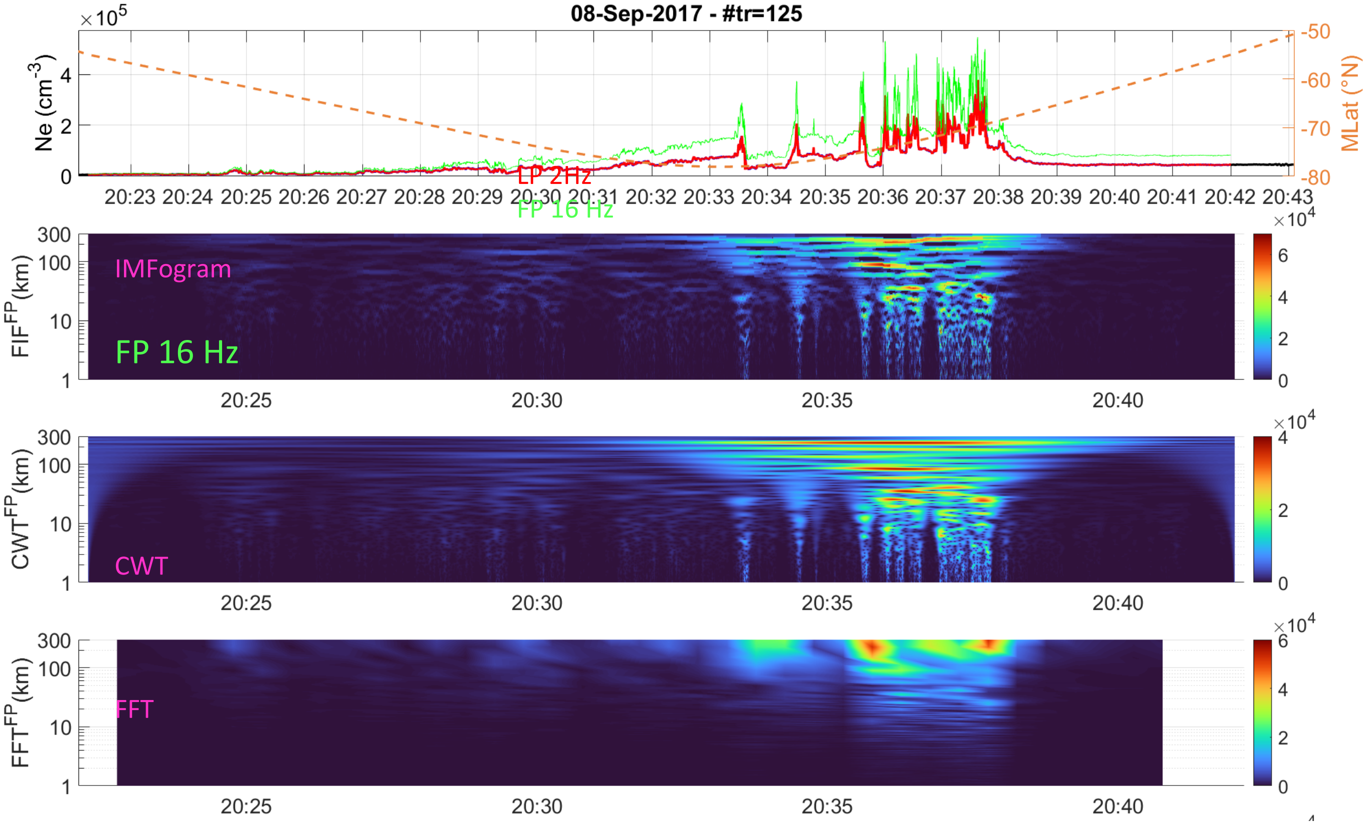


Intrinsic Mode Components (IMCs) = Intrinsic Mode Functions (IMFs)

Method

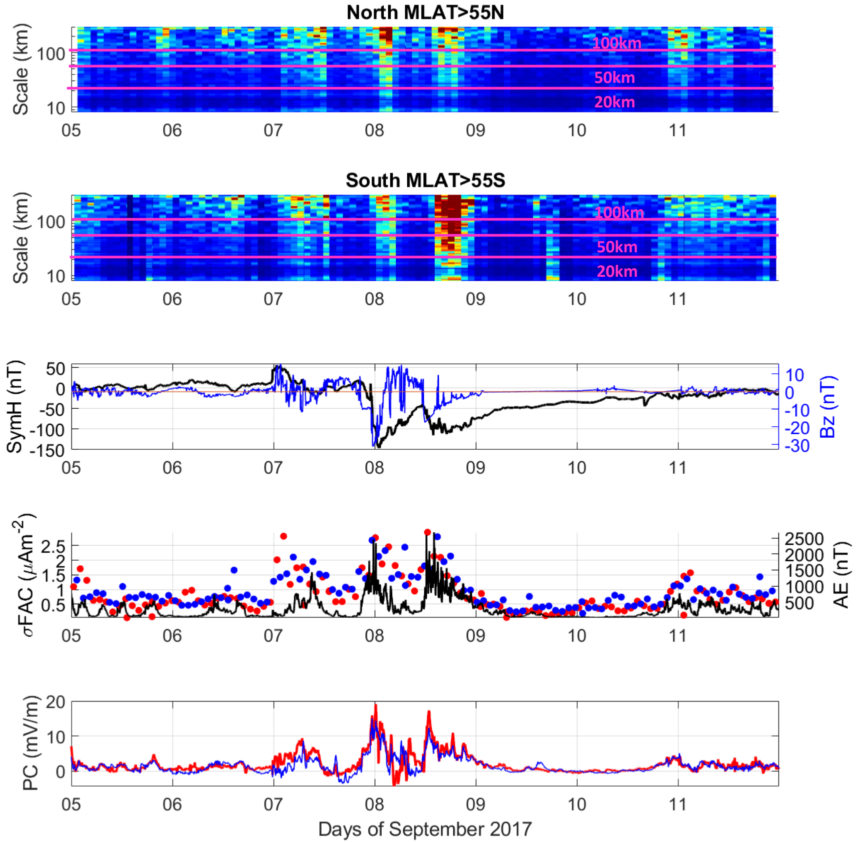

08-Sep-2017 - #tr=125
×10^5
Ne (cm^-3)
0
2
4
LP 2Hz
FP 16 Hz
MLat (°N)
-50
-60
-70
-80
20:23 20:24 20:25 20:26 20:27 20:28 20:29 20:30 20:31 20:32 20:33 20:34 20:35 20:36 20:37 20:38 20:39 20:40 20:41 20:42 20:43
|MLAT>55°|
A single track over Antarctica
FIF
FFT
IMFogram
CWT
Spectrogram
Comparison
Scale analysis

Results: comparison FIF/CWT/FFT



IMFogram has less artifacts and higher resolution in time/frequency.

Swarm-VIP: scale analysis



We identified intensification of scales in the auroral and polar regions

Other investigated storms show similar behavior

Drivers/Proxies: PC and AE

Scales at 20 km, 50 km and 100 km are often involved in the intensification

As IPIR directly provide gradNe@XXkm (XX=20, 50, 100), we decided to used that to develop the model

Urbar et al. *Submitted to Adv. Sp. Res.* 2022.

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Swarm-VIP: Model

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

$$g\big(E(y)\big) = \beta_0 + \beta_1 \cdot x_1 + \cdots + \beta_n \cdot x_n$$

The dependent variable does not have to follow a normal distribution

Equation may have a different form

Multi term model: Which combination of heliogeophysical proxies, and hence which processes, best explain the variability of ionospheric plasma observed?

- Add one independent variable to model
- Try adding other independent variables one at a time, and add the next most significant to the model (exclude any variable which is correlated with any term already in the model by more than |0.25|)
- Repeat, until there are no more statistically significant terms to add to model

Swarm-VIP: Model

Single term model: Which heliogeophysical proxies, and hence which processes, dominate? How does this vary between different regions?

Mid-latitudes	
Independent variable	**Significance Level**
Electron density	5
DOY function	5
SYM-H	5
F10.7 cm solar radio flux daily	5
IMF Bt average	5
F10.7 cm solar radio flux 27 day average	5
Kp	4
F10.7 cm solar radio flux 81 day average	4
Latitude	3
IMF By average	2
Elya solar wind coupling function average	2
Newell solar wind coupling function average	2
AE	2
IMF Bz stdev	2
IMF By stdev	2
Newell solar wind coupling function stdev	1
IMF Bt stdev	1

Auroral latitudes	
Independent variable	**Significance Level**
Electron density	5
F10.7 cm solar radio flux 27-day average	5
Kp	4
F10.7 cm solar radio flux daily	4
IMF By stdev	3
IMF By average	3
IMF Bz stdev	2
IMF Bx stdev	2
Solar wind pressure stdev	1
Latitude	1
Elya solar wind coupling function stdev	1
Newell solar wind coupling function stdev	1

What is the influence of these processes on the variability of ionospheric plasma, and how does this vary with different spatial regions?

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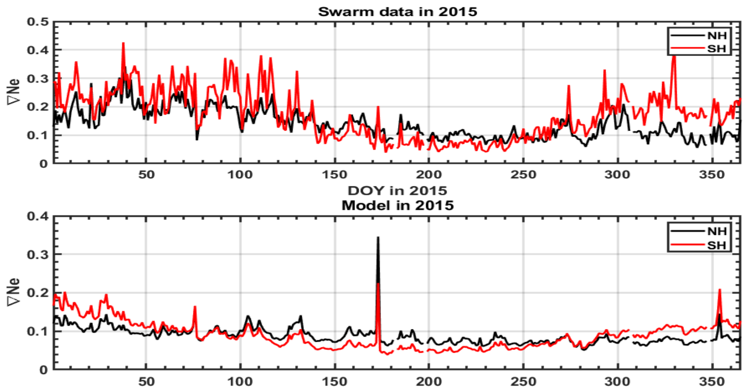
Swarm-VIP: Model

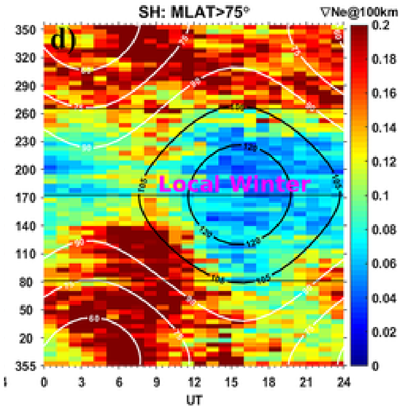
Example model: Polar model of |GradNe@100km|

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

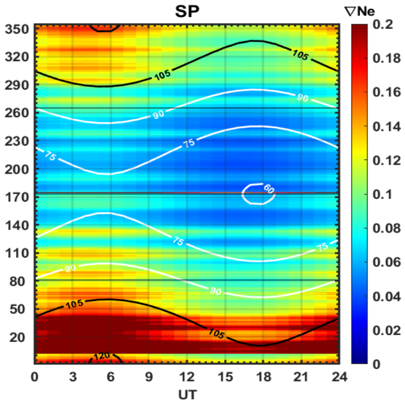
$F107_{81}$	81 day average of the F10.7cm solar flux, centred on the day to be updated
|MLAT|	Absolute value of magnetic latitude (in degrees)
SYM_D	The longitudinally symmetric disturbances to the terrestrial magnetic field perpendicular to the dipole axis

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





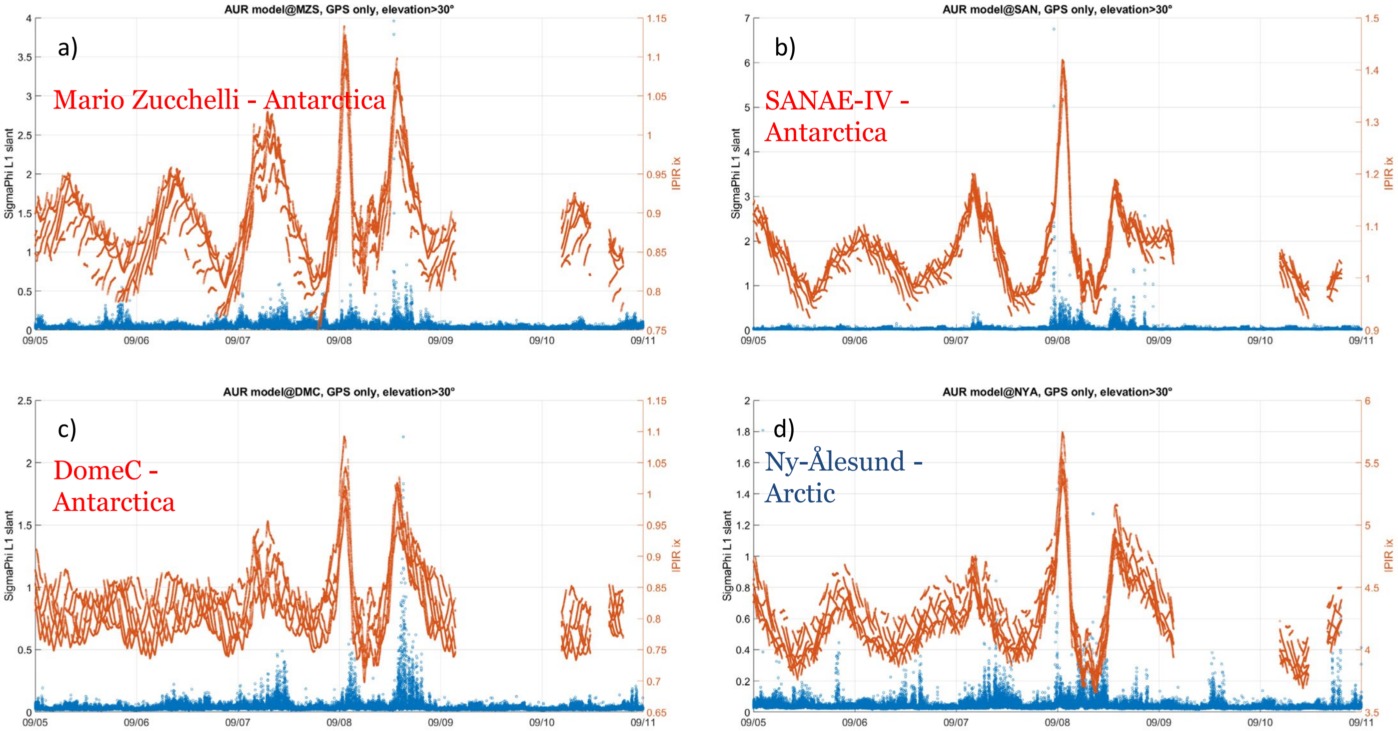
Observations



Model

Swarm-VIP: Auroral Models and ISMR data at high latitudes

Enhancements of σ_ϕ present a good correspondence with the bulk behaviour of the modelled IPIR index



Time series of σ_ϕ (blue) for every GPS satellite at elevation >30° by MZS0P (a), SAN0P (b), DMC0P (c), and NYA0P (d) receivers and of the corresponding IPIR index from **auroral** model (red), for the period 5-10 September 2017.

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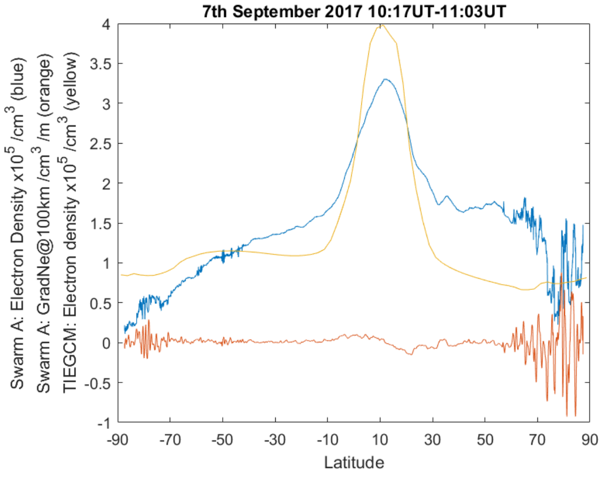
Swarm-VIP: Model – Added Value

Predictions and observations compared for four week long case studies

Model	Region	Goodness of fit				
		RMSE	rRMSE	ME	Precison	Correl.
Swarm-VIP model	Polar	2.50	0.16	0.37	0.55	0.65
	Auroral	2.23	0.15	0.15	0.70	0.62
	Mid	2.57	0.16	-0.04	0.76	0.48
	Equatorial	1.01	0.14	-0.07	0.72	0.43
TIEGCM	Polar	3.45	0.23	-1.56	0.57	0.36
	Auroral	3.22	0.22	-1.72	0.61	0.36
	Mid	2.87	0.18	0.18	0.72	0.32
	Equatorial	1.16	0.16	0.77	1.03	0.67



- Swarm VIP models show a moderate improvement over TIE-GCM in the polar, auroral and mid-latitude sectors
- TIE-GCM shows a moderate improvement over Swarm VIP models in the equatorial sector
- Sometimes TIEGCM represents the Swarm observations well, e.g, ionosphere dominated by photoionisation, but when the ionosphere is variable, TIEGCM does not always capture that variability.
- TIEGCM does not always capture ionospheric structures during quiet conditions
- Possible reason: A statistical model can respond more quickly to changes in the driving conditions
- Swarm VIP models also capture smaller scales (100km, 50km and 20km)

Swarm-VIP: Final remarks

- LEO satellites, such as Swarm, allow for addressing plasma structuring at different scales at all latitudes.

- The Swarm dataset allows for global ionospheric modeling and even longer mission will lead to even better models.

- There is a link between scintillations indices observed on the ground and modeled parameters related to plasma structuring (IPIR index).

- There is a strong potential for LEO satellites for space weather monitoring and contributing to space weateher services through both models and instant observations.

- Swarm-VIP model will be soon released! Everyone is welcome to join our efforts!

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