SWARM VIP

SWARM SPACE WEATHER

VARIABILITY OF IONOSPHERIC PLASMA

Swarm-VIP | Variability of Ionospheric Plasma Observed by Swarm

Swarm-VIP | Variability of Ionospheric Plasma

Swarm-VIP Team

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UNIVERSITY OF BIRMINGHAM
SERENE Space Environment & Radio Engineering
SWARM VIP SWARM SPACE WEATHER VARIABILITY OF IONOSPHERIC PLASMA

Swarm-VIP-Dynamic | Variability, Irregularities, and Predictive capabilities for the Dynamic ionosphere

Swarm-VIP-Dynamic Team

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Swarm-VIP | Variability of Ionospheric Plasma

Swarm-VIP Project:

Investigate the variability in ionospheric plasma on multiple spatial scales

Generalised Linear Modelling:

Determines the relative importance of the driving processes & which combination of driving processes best represent the observed variability

Create a model of the variability of ionospheric plasma

Image Credit: ESA

UiO University of Oslo

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Generalised Linear Modelling | Method

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

$E(y)$ 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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Measure of the variability of the electron density: Level 2 data product IPDxIRR_2F from IPIR

|Grad_Ne@100km|: The electron density gradient in a running window calculated via linear regression over 27 data points for the 2 Hz electron density data

|Grad_Ne@50km|: The electron density gradient in a running window calculated via linear regression over 13 data points for the 2 Hz electron density data

|Grad_Ne@20km|: The electron density gradient in a running window calculated via linear regression over 5 data points for the 2 Hz electron density data

Electron Density: Measured by the Langmuir probe

IPIR Index: The product of the rate of change density index in 10 seconds ($\mathrm{RODI}10s$) and the standard deviation of the electron density in a running window of 10 seconds ($A(n_e)_{10s}$):

$$\mathrm{IPIR_{ix}} = \mathrm{RODI}10s \cdot A(n_e)_{10s}$$

Swarm Observations | Variability of Ionospheric Plasma

Measure of the variability of the electron density: Level 2 data product IPDxIRR_2F from IPIR

|Grad_Ne@100km|: The electron density gradient in a running window calculated via linear regression over 27 data points for the 2 Hz electron density data

|Grad_Ne@50km|: The electron density gradient in a running window calculated via linear regression over 13 data points for the 2 Hz electron density data

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Electron Density: Measured by the Langmuir probe

IPIR Index: The product of the rate of change density index in 10 seconds ($\mathrm{RODI}10s$) and the standard deviation of the electron density in a running window of 10 seconds ($A(n_e)_{10s}$):

$$\mathrm{IPIR}_{\mathrm{ix}} = \mathrm{RODI}10s \cdot A(n_e)_{10s}$$

Latitudinal region: Modelling polar, auroral, mid-latitude and equatorial regions separately

Two years of data from Swarm A, covering 16th July 2014 – 15th July 2015 & 1st January – 31st December 2017

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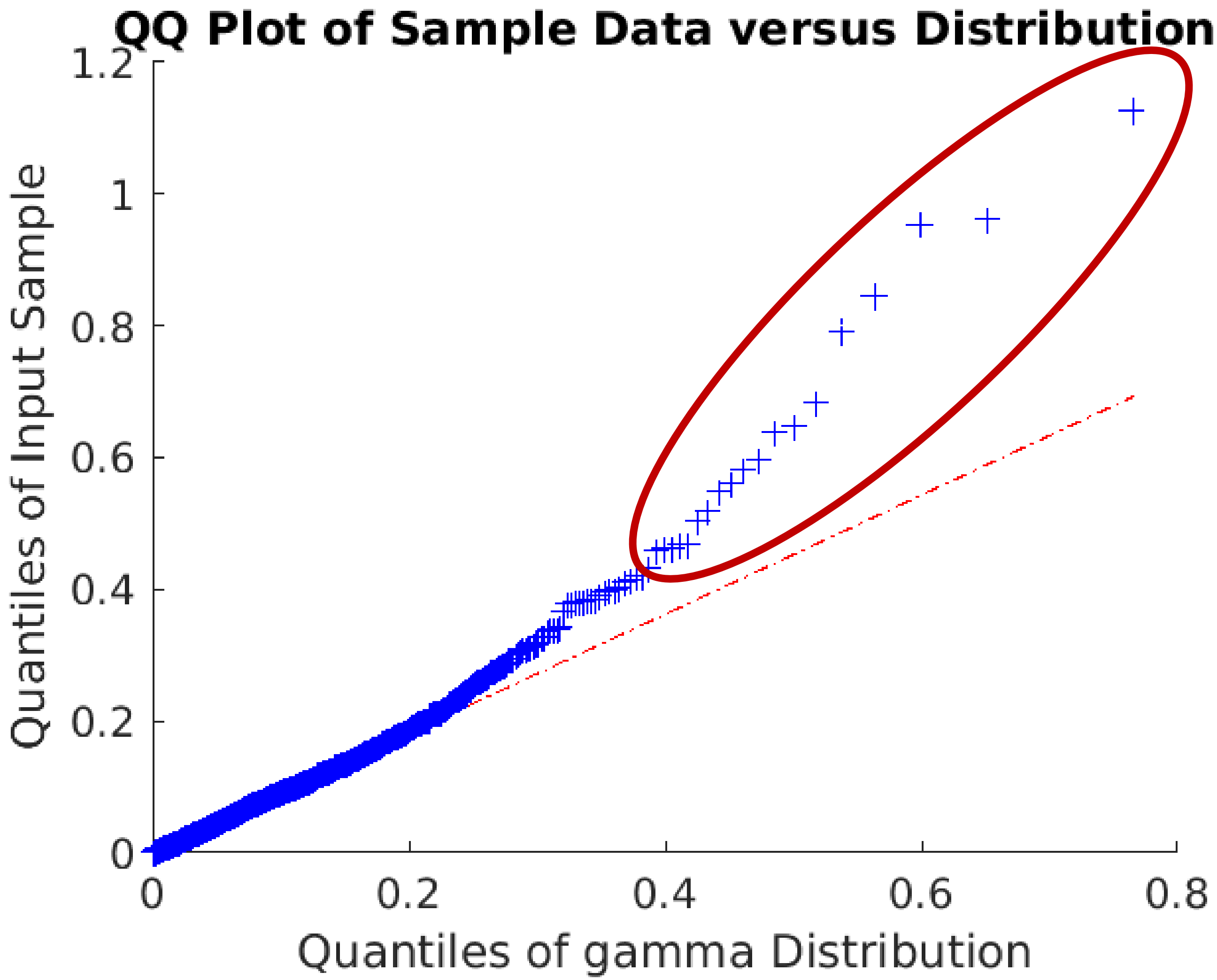
Model Development | Choice of Distribution



Distributions Trialled: Normal, Half-Normal, Birnbaum Saunders, Burr, Exponential, Extreme Value, Gamma, Inverse Gaussian, Kernel, Logistic, Loglogistic, Lognormal, Nakagami, Rician, Stable, tLocation Scale and Weibull

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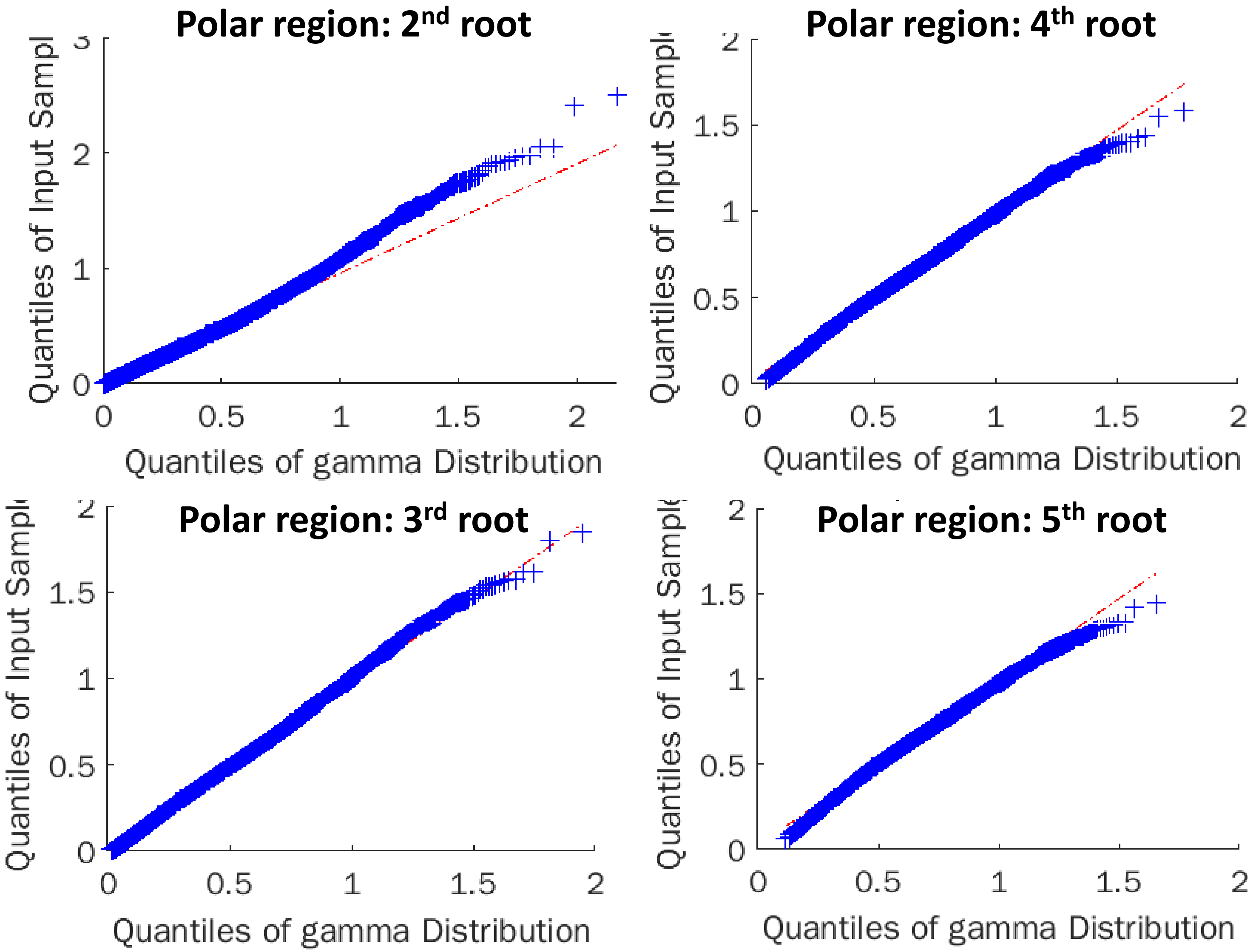
Model Development | Choice of Distribution

Example: |Grad_Ne@100km| in the polar region: Gamma distribution



Transforming the Data

Model a function of the dependent variable

Trialled logarithms, exponentials, powers and roots

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Generalised Linear Modelling | Explanatory Variables

Heliogeophysical proxies

Interplanetary Magnetic Field (IMF): Bt, Bx, By, |By|, Bz and clock angle. Mean and standard deviation measured over a 2 hour interval, starting 2 hours before the observation of the dependent variable.

Solar wind: Mean and standard deviation of bulk speed, density, pressure and Interplanetary Electric Field (IEF) measured over a 2 hour interval, starting 2 hours before the observation of the dependent variable.

Solar wind coupling functions: Newell (left) and E_{LYA} (right). Mean and standard deviation of these measured over a 2 hour interval, starting 2 hours before the observation of the dependent variable.

$$v^{4/3} \cdot B_T^{2/3} \cdot sin^{8/3}\left(\frac{\theta_c}{2}\right) \qquad\qquad v{B_T}^{\frac{1}{2}} sin^2\left(\frac{\theta_c}{2}\right)$$

v is the solar wind velocity, B_T is the magnitude of the IMF and θ_c is the clock angle.

Geomagnetic Activity: AE, AL, AU, ASY-D, ASY-H, SYM-D, SYM-H, Kp and Ap

Solar Activity: F10.7 cm solar flux (daily, 27 day median and 81 day median)

Other: Polar cap index (North), GLAT, MLAT, MLT and SZA

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Generalised Linear Modelling | Method

Generalised Linear Model

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

Gamma distribution

Logarithmic link function

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

- Add the heliogeophysical proxy which best explains the variability to the model
  (the most statistically-significant proxy)
- Add the heliogeophysical proxy which best explains the remaining variability
  (the next most statistically significant, 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 statistically significant at the 5% level)

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Swarm-VIP Model | Models Created

Example Model: Polar model of $|Grad\_Ne@100km|$

$$\sqrt[3]{|Grad\_Ne@100km|} = \exp\begin{pmatrix} \beta_0 + \beta_1 \cdot F107_{81} + \beta_2 \cdot SZA + \beta_3 \cdot fDOY + \beta_4 \cdot Kp \\ +\beta_5 \cdot |MLAT| + \beta_6 \cdot B_x + \beta_7 \cdot SW\_Den + \beta_8 \cdot SYM\_D \end{pmatrix}$$

$F107_{81}$	81 day average of the F10.7cm solar flux, centred on the day to be updated
SZA	Solar Zenith Angle
fDOY	A sine function based on the day of year, going from -1 at midwinter to +1 at midsummer
Kp	Planetary K-index
|MLAT|	Absolute value of magnetic latitude (in degrees)
B_x	The average value of the x-component of the Interplanetary Magnetic Field (in nT), across a two hour window, starting two hours before the observation to be updated
SW_Den	As B_x, but for the solar wind proton number density (in # cc^{-1})
SYM_D	The longitudinally symmetric disturbances to the terrestrial magnetic field perpendicular to the dipole axis

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Swarm-VIP Model | Optimisation & Evaluation

Database

1st January 2014 – 15th July 2014: Optimisation and Evaluation

16th July 2014 – 15th July 2015: Training

16th July 2015 – 31st December 2016: Optimisation and Evaluation

1st January 2017 – 31st December 2017: Training

1st January 2018 – 28th February 2018: Optimisation and Evaluation

Odd DOYs used for optimisation and even DOYs used for evaluation

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Swarm-VIP Model| Optimisation & Evaluation

Optimisation: Refit models. Identify any terms which are no-longer statistically-significant at the 5% level. Remove these.

AIC is based on the trade off between model performance and model complexity

$$AIC = -2 \cdot ln(L) - 2 \cdot k$$

L is the log likelihood, k is the number of parameters

Does the addition of successive terms to the model reduce the AIC? If not, then remove terms that increase the AIC

Do not remove terms based on the AIC if there is no longer a measure of LAT, MLT/ST/SZA, Solar Activity & geomagnetic activity/solar wind. The items in each category are:

- **LAT:** LAT, MLAT
- **MLT/ST/SZA:** MLT, LT, SZA
- **Solar Activity:** F10.7cm Solar Radio Flux, Sunspot Number
- **Geomagnetic activity/solar wind:** Any IMF, Any measure of the solar wind or a coupling function, any geomagnetic index

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Swarm-VIP Model| Optimisation

Optimisation Example: Polar model of $|Grad\_Ne@100km|$

$$\sqrt[3]{|Grad\_Ne@100km|} = \exp\begin{pmatrix} \beta_0 + \beta_1 \cdot F107_{81} + \beta_2 \cdot SZA + \beta_3 \cdot fDOY + \beta_4 \cdot Kp \\ +\beta_5 \cdot |MLAT| + \beta_6 \cdot B_x + \beta_7 \cdot SW\_Den + \beta_8 \cdot SYM\_D \end{pmatrix}$$

Re-fit model and remove any terms which are no-longer significant: Lose two terms

$$\sqrt[3]{|Grad\_Ne@100km|} = \exp\begin{pmatrix} \beta_0 + \beta_1 \cdot F107_{81} + \beta_2 \cdot SZA + \beta_3 \cdot fDOY + \beta_4 \cdot Kp \\ +\beta_5 \cdot |MLAT| + \beta_7 \cdot SW\_Den \end{pmatrix}$$

Is this level of complexity justified? Lose another term

$$\sqrt[3]{|Grad\_Ne@100km|} = \exp\begin{pmatrix} \beta_0 + \beta_1 \cdot F107_{81} + \beta_2 \cdot SZA + \beta_3 \cdot fDOY + \beta_4 \cdot Kp \\ +\beta_5 \cdot |MLAT| \end{pmatrix}$$

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Swarm-VIP Model | Evaluation

Accuracy: RMSE

$$RMSE = \sqrt{\frac{1}{N-d}\sum_{i=1}^{N}(M_i - O_i)^2}$$

Expressed on a relative scale (divide RMSE by median of observations). If rRMSE=1 then the differences between observations and predictions are the same size as the predictions.

Bias: Mean Error

$$ME = \overline{M} - \overline{O}$$

Positive: Model consistently overpredicts. Negative: Model consistently underpredicts

Precision: Ratio of the standard deviations

$$P_{\sigma,\text{ratio}} = \frac{\sigma_M}{\sigma_O}$$

If this is greater than 1, then the average standard deviation of the model values is greater than of the observed values. There is too much spread (noise) in the model values. If it is less than 1, then there is not enough spread in the model values (model is overfitted).

Association: Pearson Linear Correlation Coefficient

$$R = \frac{\sum\left(O_i - \overline{O}\right)\left(M_i - \overline{M}\right)}{\sqrt{\sum\left(O_i - \overline{O}\right)^2 \sum\left(M_i - \overline{M}\right)^2}}$$

Model values are denoted by M, with individual values with the number set listed as M_i. Observational values are given the variable O, with individual data points called out by O_i. The total number of pairs in the data-model set is N.

Liemohn et al., RMSE is not enough: Guidelines to robust data-model comparisons for magnetospheric physics, JASTP, 218, 105624, 2021

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Swarm-VIP Model | Evaluation

Goodness of fit statistics

Model		Goodness of fit			
Region	Dependent Variable	rRMSE	rME	Precision	Correlation
Polar	GradNe@100km	0.47	0.00	0.37	0.36
	GradNe@50km	0.49	0.00	0.37	0.35
	GradNe@20km	0.58	0.00	0.31	0.30
	IPIR Index	0.24	0.00	0.46	0.45
	Ne	0.16	0.00	0.76	0.75
Auroral	GradNe@100km	0.47	0.00	0.31	0.31
	GradNe@50km	0.18	0.00	0.28	0.28
	GradNe@20km	0.98	0.01	0.26	0.24
	IPIR Index	0.24	0.00	0.37	0.36
	Ne	0.15	0.00	0.76	0.75
Mid Latitude	GradNe@100km	0.19	0.00	0.24	0.23
	GradNe@50km	0.19	0.00	0.22	0.21
	GradNe@20km	0.98	0.00	0.20	0.20
	IPIR Index	0.30	0.00	0.33	0.34
	Ne	0.16	0.00	0.73	0.68
Equatorial	GradNe@100km	0.43	-0.05	0.57	0.30
	GradNe@50km	0.21	-0.02	0.56	0.29
	GradNe@20km	1.16	-0.12	0.61	0.28
	IPIR Index	0.34	-0.04	0.48	0.19
	Ne	0.16	-0.03	0.83	0.53

rRMSE: Substantially less than 1 in most cases

rME: No significant bias

Precision: Not enough spread in model values

Correlation: Between 0.20 and 0.75

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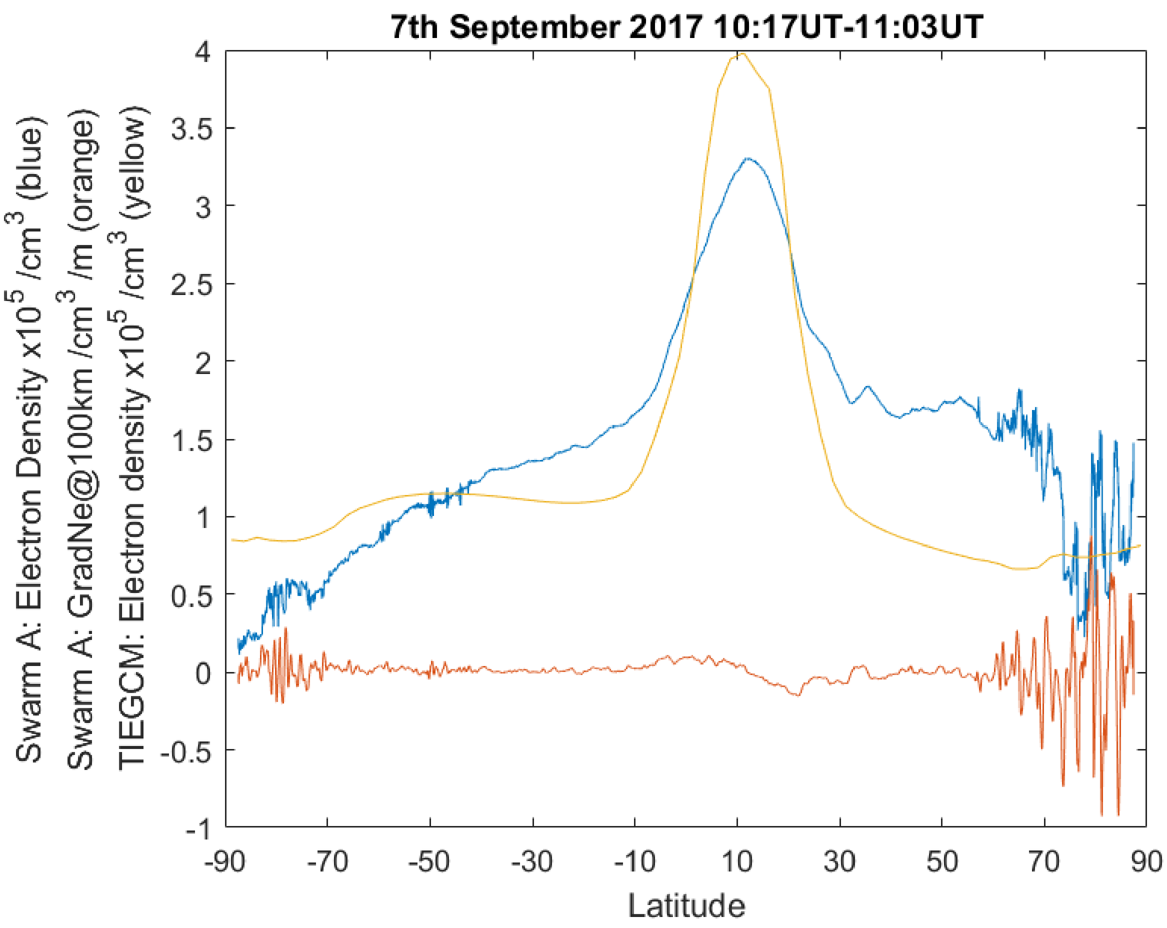
TIEGCM Comparisons | Along-track comparisons

TIE-GCM simulations: Model predictions on a grid of:

- 2.5° latitude
- 2.5° longitude
- Pressure levels separated by 0.25 scale heights
- one hour

TIEGCM captures some, but not all, of the ionospheric variability



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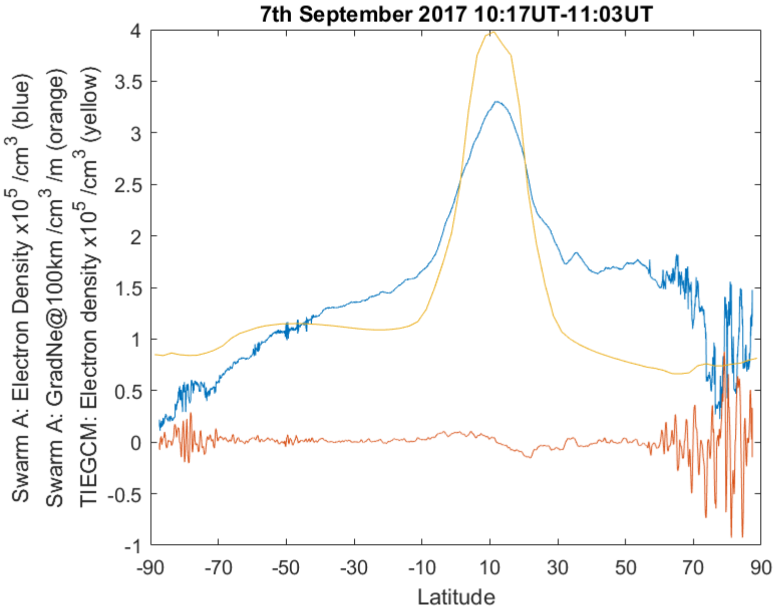
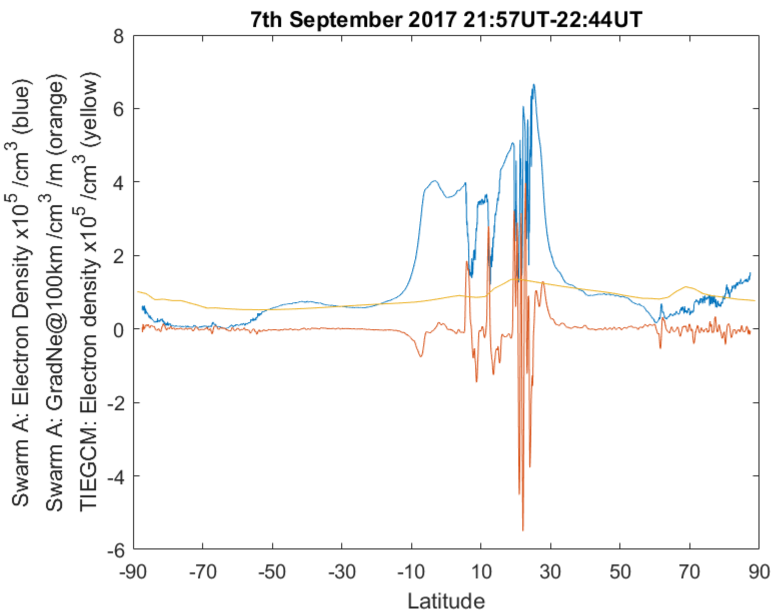
TIEGCM Comparisons | Along-track comparisons

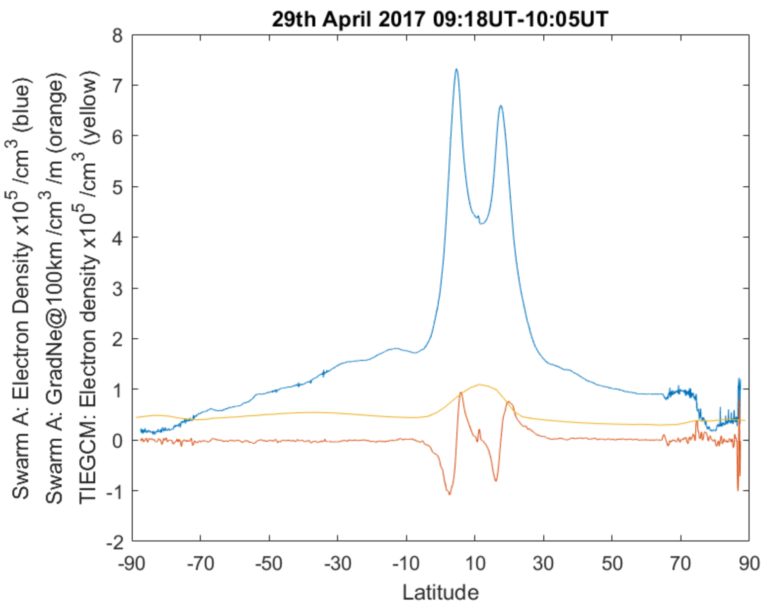
There are occasions when TIEGCM represents the Swarm observations well, such as when the ionosphere is dominated by photoionisation

When the ionosphere is variable, TIEGCM does not always capture that variability

TIEGCM does not always capture ionospheric structures even during quiet conditions







TIEGCM Comparisons | Along-Track Comparisons

Predictions and observations of electron density compared for four week long case studies

Model	Region	Goodness of fit			
		rRMSE	rME	Precison	Correl.
Swarm-VIP	Polar	0.16	0.02	0.55	0.65
	Auroral	0.15	0.01	0.70	0.62
	Mid	0.16	0.00	0.76	0.48
	Equatorial	0.14	-0.01	0.72	0.43
TIEGCM	Polar	0.24	-0.11	0.37	0.22
	Auroral	0.24	-0.14	0.42	0.22
	Mid	0.17	-0.03	0.46	0.38
	Equatorial	0.13	0.07	0.81	0.69

Dates & orbits

4th – 10th Sept. 2017: 10-22 LT, Major geomagnetic storm

26th April – 2nd May 2017: 10-22 LT

13th – 20th August 2017: 00-12 LT

23th – 29th October 2017: 06-18 LT

- **Correlations:** Swarm VIP models show a moderate improvement over TIE-GCM in the polar, auroral and mid-latitude sectors.
- **Correlations:** TIE-GCM shows a moderate improvement over Swarm VIP models in the equatorial sector
- **Bias:** Less bias in Swarm VIP models

Spogli, L., et al., (2024). Statistical Models of the Variability of Plasma in the Topside Ionosphere: 2: Performance Assessment, J. Space Weather Space Clim., swsc230023. doi: 10.1051/swsc/2024003

Jin et al., Performance Assessment for Statistical Models of the Ionospheric Variability in the Topside Ionosphere, poster, this meeting

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Swarm-VIP Model | Evaluation

Goodness of fit statistics

Model		Goodness of fit			
Region	**Dependent Variable**	**rRMSE**	**rME**	**Precision**	**Correlation**
Polar	GradNe@100km	0.47	0.00	0.37	0.36
	GradNe@50km	0.49	0.00	0.37	0.35
	GradNe@20km	0.58	0.00	0.31	0.30
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Auror[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Mid Lati[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	IPIR Index	0.30	0.00	0.33	0.34
	Ne	0.16	0.00	0.73	0.68
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	IPIR Index	0.34	-0.04	0.48	0.19
	Ne	0.16	-0.03	0.83	0.53

Not capturing all of the variability

- **Can only capture the deterministic component**
- **The explanatory variables are proxies for processes, not the processes themselves**
- **Is there a missing process: No thermospheric term in models**

rRMSE: Substantially less than 1 in most cases

rME: No significant bias

Precision: Not enough spread in model values

Correlation: Between 0.20 and 0.75

Swarm VIP Dynamic | Ionosphere-Thermosphere Coupling

DNSxPOD_2_ Level 2 data product which estimates the neutral density based on Precise Orbit Determination (POD)

Cadence of 30 seconds, but ~20 minutes of data used for each data point

ACCxCAL2 Level 2 data product which includes the along track accelerations

Cadence of 1 second

DNSxACC_2_ Level 2 data product which estimates the neutral density based on the accelerations

Cadence of 10 seconds

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Swarm-VIP-Dynamic | Ionosphere-Thermosphere Coupling

Polar model of $|Grad\_Ne@100km|$

Original model: No thermospheric information

$$\sqrt[3]{|Grad\_Ne@100km|} = \exp\begin{pmatrix}\beta_0 + \beta_1 \cdot F10.7_{81} + \beta_2 \cdot SZA + \beta_3 \cdot fDOY + \beta_4 \cdot Kp \\ +\beta_5 \cdot |MLAT|\end{pmatrix}$$

Densities inferred from Precise Orbit Determination: DNSxPOD_2_

$$\sqrt[3]{|Grad\_Ne@100km|} = \exp\begin{pmatrix}\beta_0 + \beta_1 \cdot Density_{POD} + \beta_2 \cdot fDOY + \beta_3 \cdot SZA \\ +\beta_4 \cdot Clock + \beta_5 \cdot A_p + \beta_6 \cdot B_x + \beta_7 \cdot Clock_{sd}\end{pmatrix}$$

Along track accelerations: ACCxCAL2

$$\sqrt[3]{|Grad\_Ne@100km|} = \exp\begin{pmatrix}\beta_0 + \beta_1 \cdot Acc\_X + \beta_2 \cdot SZA + \beta_3 \cdot |MLAT| + \beta_4 \cdot fDOY \\ +\beta_5 \cdot SW\_Vel + \beta_6 \cdot B_y sd\end{pmatrix}$$

Densities inferred from accelerometers: DNSxACC_2_

$$\sqrt[3]{|Grad\_Ne@100km|} = \exp\begin{pmatrix}\beta_0 + \beta_1 \cdot Density_{acc} + \beta_2 \cdot |MLAT| + \beta_3 \cdot SZA \\ +\beta_4 \cdot fDOY + \beta_5 \cdot SW\_Vel + \beta_6 \cdot B_y sd\end{pmatrix}$$

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Swarm-VIP-Dynamic | Ionosphere-Thermosphere Coupling

Example Model: Polar model of $|Grad\_Ne@100km|$

|Grad_Ne@100km| in the polar region		Version: No density	DNS_POD	ACC	DNS_ACC
Explanatory variables	SZA	■	■	■	■
	fDOY	■	■	■	■
	|MLAT|	■		■	■
	$F10.7_{81}$	■			
	B_x		■		
	$B_y sd$			■	■
	Clock		■		
	$Clock_{sd}$		■		
	SW_Vel			■	■
	Kp	■			
	Ap		■		

SZA — Solar Zenith Angle

fDOY — A sine function based on the day of year, going from -1 at midwinter to +1 at midsummer

|MLAT| — Abs. value of magnetic latitude (degrees)

$F107_{81}$ — 81 day average of the F10.7cm solar flux, centred on the day to be updated

B_x — The average value of the x-component of the Interplanetary Magnetic Field (in nT), across a two hour window, starting two hours before the observation

Clock — As Bx for clock angle

$Clock_{sd}$ — As Clock, but standard deviation

SW_Den — As B_x, but for the solar wind velocity (in km s^{-1})

Kp — Planetary K-index

Ap — Geomagnetic index

Swarm-VIP-Dynamic | Ionosphere-Thermosphere Coupling

Example Model: Polar model of $|Grad\_Ne@100km|$

|Grad_Ne@100km| in the polar region		Version: No density	DNS_POD	ACC	DNS_ACC
Explanatory variables	SZA	■	■	■	■
	fDOY	■	■	■	■
	|MLAT|	■		■	■
	$F10.7_{81}$	■			
	B_x		■		
	$B_y sd$			■	■
	Clock		■		
	$Clock_{sd}$		■		
	SW_Vel			■	■
	Kp	■			
	Ap		■		

Change in goodness of fit statistics is small

- Need to include lags
- Some issues with data selection, based upon quality flags
- Interhemispherical and longitudinal effects still to be considered
- Swarm-VIP-Dynamic includes substantial amounts of work on model development

Model		Goodness of fit			
Dependent variable	**Version**	**rRMSE**	**rME**	**Precision**	**Correlation**
|Grad_Ne@100km| in the polar region	No thermosphere	0.47	0.00	0.37	0.36
	DNS_POD	0.50	0.00	0.44	0.36
	ACC	0.49	0.00	0.34	0.31
	DNS_ACC	0.48	0.00	0.39	0.34

Summary | Swarm-VIP-Dynamic

Statistical models allow reasonable predictions of ionospheric plasma, and the variability in this plasma, to be predicted

The models have successes and they do not show significant bias

The models do not capture all of the ionospheric variability; they cannot capture stochastic variations and there is at least one missing driver, the thermosphere

Performance Assessment: Jin et al., Performance Assessment for Statistical Models of the Ionospheric Variability in the Topside Ionosphere, poster, this meeting

Swarm-VIP-Dynamic

Will address limitations of Swarm-VIP models, plus many other questions

Miloch et al., 15:30 today

Models from the Swarm-VIP project

Wood, A. G. et al. (2024). Statistical Models of the Variability of Plasma in the Topside Ionosphere: 1. Development and Optimisation, J. Space Weather Space Clim., in press, swsc230022.

Spogli, L., et al., (2024). Statistical Models of the Variability of Plasma in the Topside Ionosphere: 2: Performance Assessment, J. Space Weather Space Clim., swsc230023. doi: 10.1051/swsc/2024003

SWARM VIP
SWARM SPACE WEATHER
VARIABILITY OF IONOSPHERIC PLASMA