

# Optimising AENEAS: The UK Operational Model for Space Weather Forecasting

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## 1. Why do we care about the Upper Atmosphere?

The **thermosphere** is the **neutral layer** of Earth's upper atmosphere above ~100 km.

Solar extreme ultraviolet (EUV) and X-ray radiation **photoionise** neutral particles in the thermosphere, forming the **ionosphere**.

The thermosphere and ionosphere are strongly coupled through ion-neutral interactions.

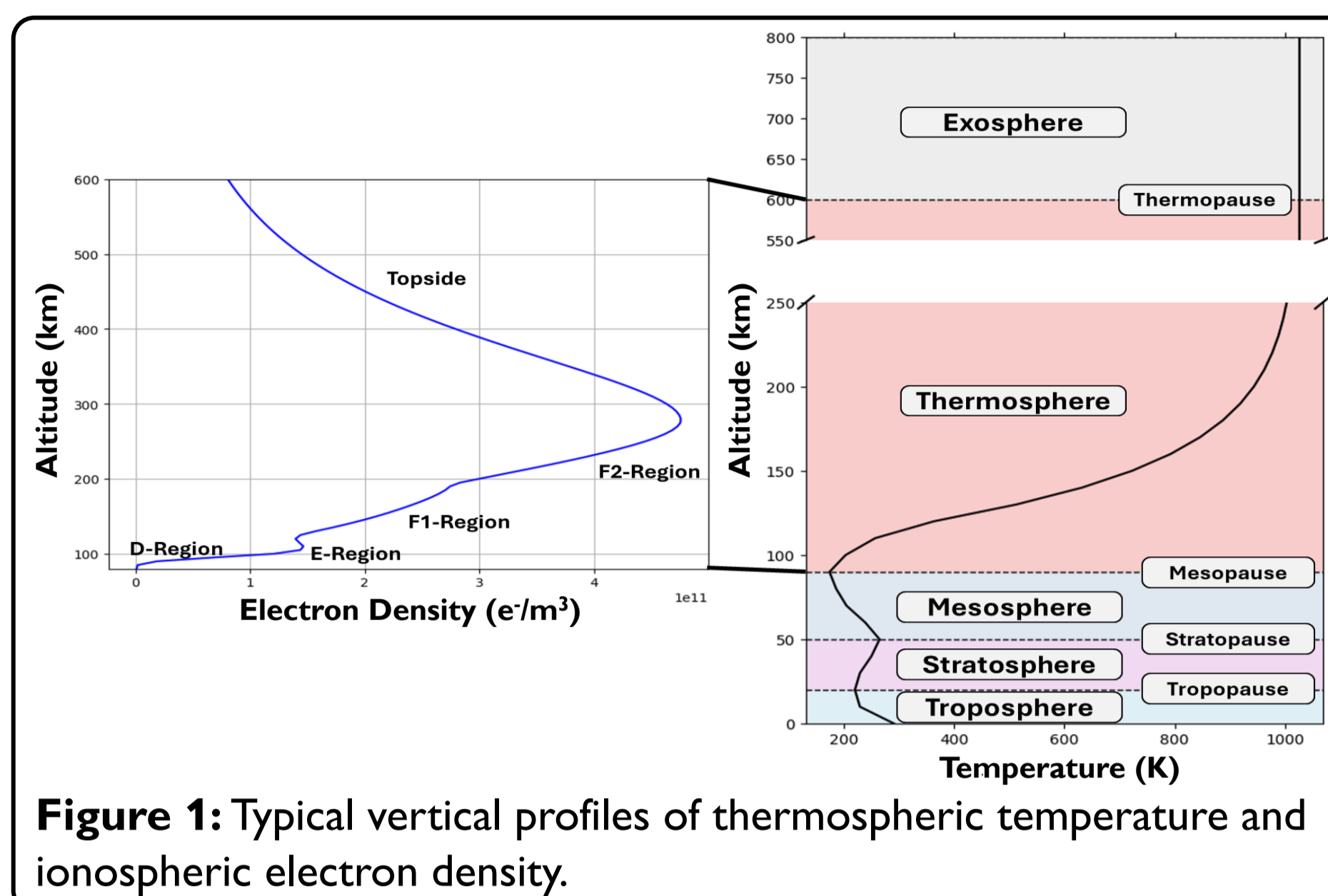


Figure 1: Typical vertical profiles of thermospheric temperature and ionospheric electron density.

Accurate modelling of the coupled ionosphere-thermosphere (I-T) system is essential for:

- High Frequency (HF) radio communication,
- Global Navigation Satellite Systems (GNSS),
- Satellite orbit prediction.

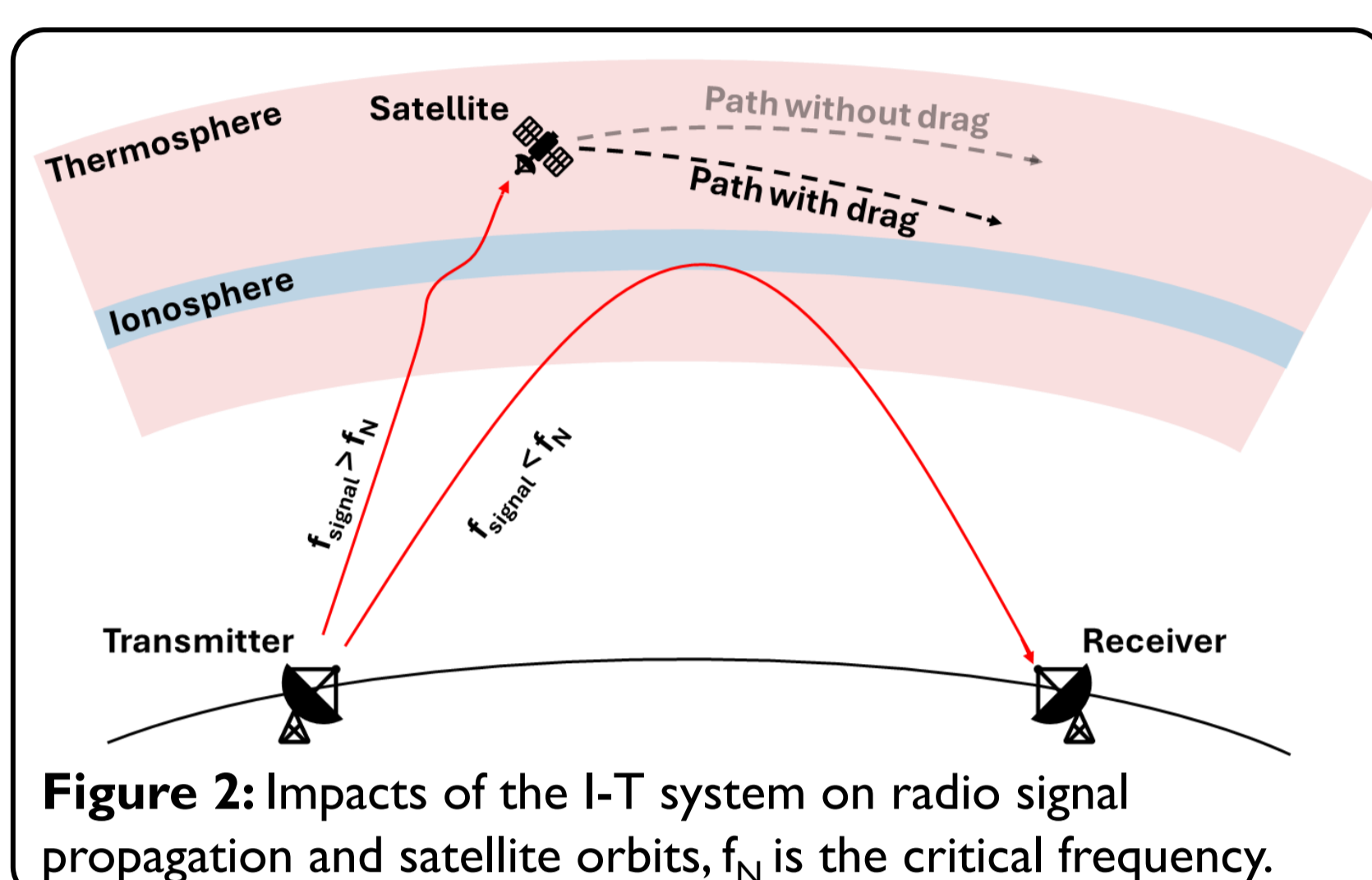


Figure 2: Impacts of the I-T system on radio signal propagation and satellite orbits,  $f_N$  is the critical frequency.

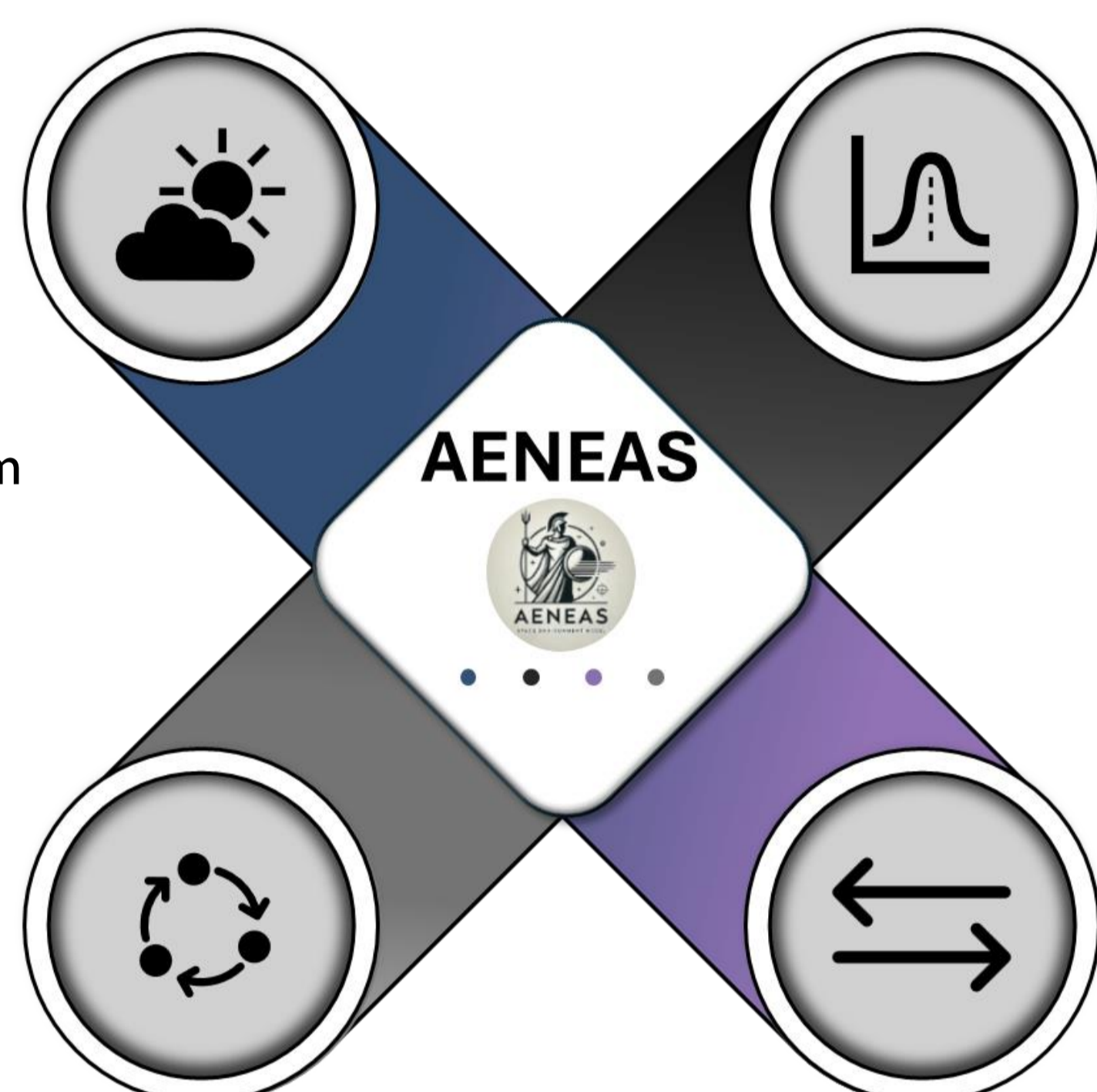
## 2. AENEAS: Model Overview

### Background Model

- Bottomside:** Physics-based TIE-GCM (97-600 km)
- Scope:** Couples ionosphere and thermosphere dynamics
- Topside:** Extended to 20200 km using NeQuick

### Driving Parameters

- Geomagnetic Activity:** Driven by  $K_p$  index
- Solar Forcing:** Driven by F10.7 flux



### Data Assimilation (DA)

- DA Scheme:** Local Ensemble Transform Kalman Filter (LETKF)
- Ensemble:** 32 TIE-GCM members
- Data:** GNSS & radio occultation TEC, in situ, and ionosonde data

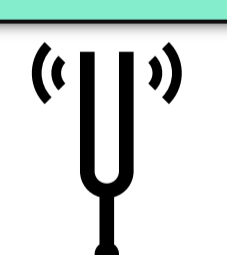
### Output

- Temporal:** 15-min assimilation window
- Spatial:** 5.0° x 5.0° lat-lon grid (optionally 2.5° x 2.5°), variable height resolution

Figure 3: The Advanced Ensemble Networked Assimilation System (AENEAS) [1] is an operational data assimilation model deployed at the UK Met Office, designed to nowcast and forecast the upper atmosphere in near-real-time.

## 3. Motivation & Objectives

1



**Model Sensitivity**  
AENEAS performance is controlled by **tunable parameters** governing **ensemble generation** and **data assimilation**.

2



**Research Gap**  
Parameters in the latest model version remain **unoptimised** and their impact on performance is not well understood.

3



**This Study**  
Comprehensive **optimisation** of AENEAS to identify an **optimal model configuration** and **benchmark** its performance.

4



**Outcomes**

- Improved ionospheric model performance
- Enhanced understanding of parameter sensitivity
- Foundation for future validation

## 4a. Optimisation Framework

### Optimisation Time Period:

8<sup>th</sup> February 2025:

- Geomagnetically quiet ( $K_p < 4$ ),
- Moderate solar activity ( $163 \text{ sfu} \leq F10.7 \leq 173 \text{ sfu}$ ),
- Baseline case for model optimisation under quiet conditions.

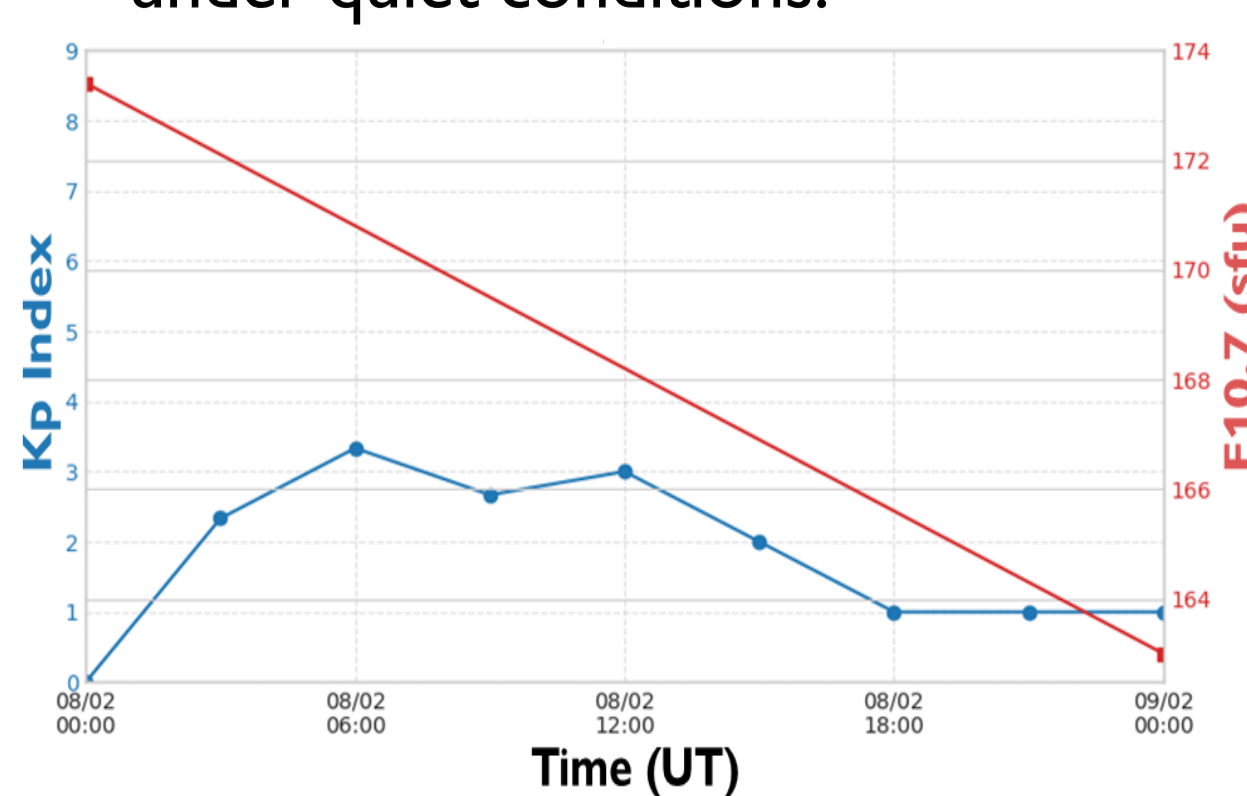


Figure 4: Kp and F10.7 for the optimisation period (8 Feb 2025).

### GNSS sTEC Assimilation & Preprocessing:

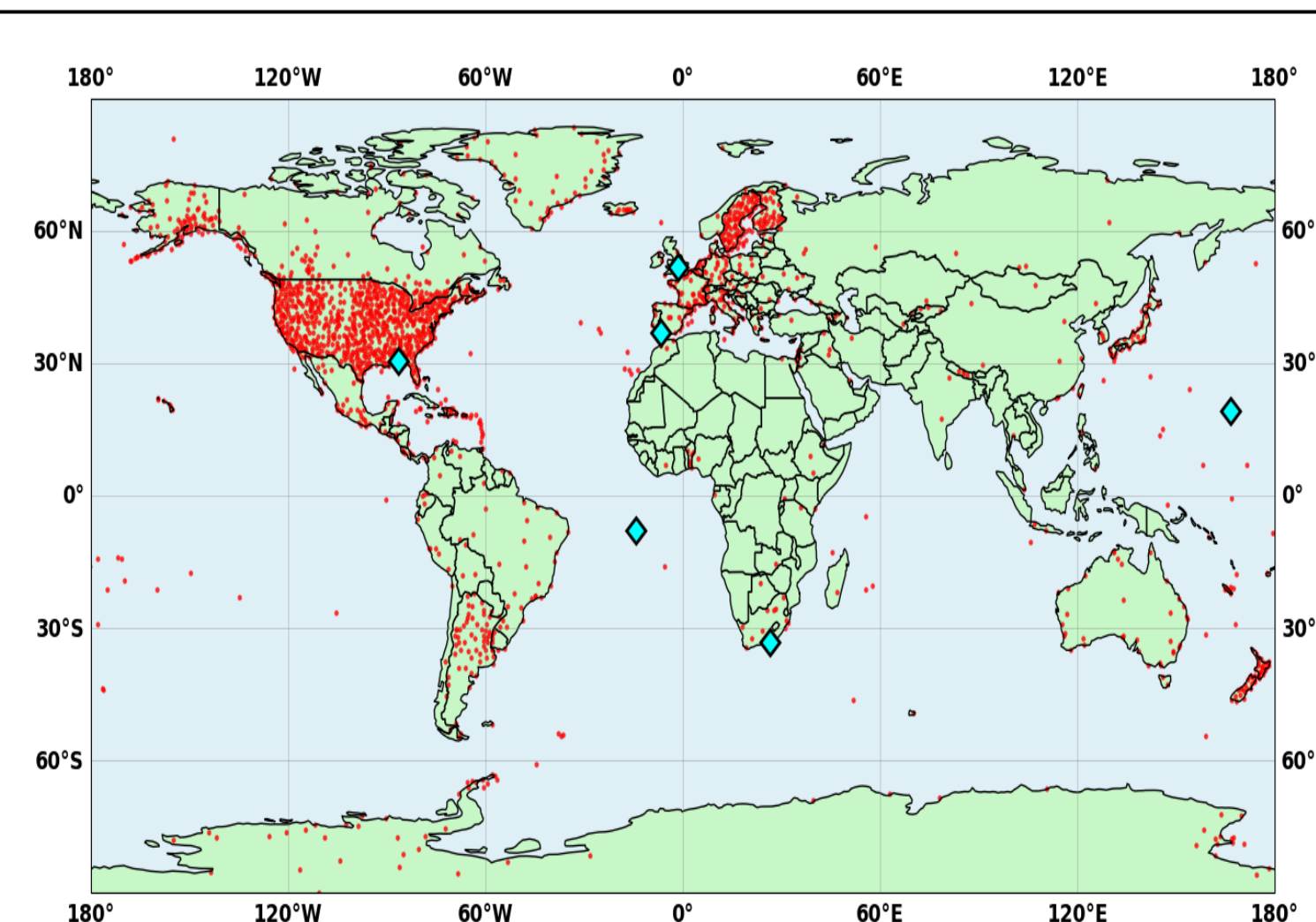
- Slant Total Electron Content (sTEC) from Madrigal database [2].
- Remove low-elevation observations ( $<15^\circ$ ) to reduce multipath effects.
- Average to 5-min intervals to thin data and reduce temporal correlation.
- Define observation uncertainty ( $\epsilon_{sTEC}$ ) as,  

$$\epsilon_{sTEC} = \sqrt{1.5^2 + (10\sigma_{sTEC})^2}, \quad (1)$$
 $\sigma_{sTEC}$  is the standard deviation of sTEC within each 5-min window.

### Comparison Datasets:

Model output compared to foF2 (F2 critical frequency) and hmF2 (F2 peak height) measurements, derived from hand-scaled ionograms.

Figure 5: Ionosonde stations used for model comparison on 8 Feb 2025 (blue diamonds), with assimilated GNSS receivers shown in red.



## 4b. Tuning Parameter Optimisation

- Parameters tuned **sequentially**, with multiple candidate values tested at each stage.
- Performance evaluated **using time series, global maps, and statistical metrics**.
- Best-performing configuration retained** for the next stage; poor or unstable configurations rejected.

	Description	Effect	Risk	FS	Opt
Data Removal	Remove data outside $3\sigma$ from ensemble mean	Remove outlying data	Remove useful data	On	Off
TIEGCM Timestep	Internal timestep to solve governing equations	Increase numerical stability	Change model output	30 s	30 s
Error Inflation	Multiply assimilated data uncertainty	Reduce assimilated data impact	Limited updates from data	1x	10x
F10.7 Spread	Widen range of possible F10.7 values for members	Model can explore more possibilities	Drive a poor ensemble	3.0	6.0
Covariance Inflation	Inflate error assigned to background model	Fine tune assimilated data influence	Runaway inflation	1.1	1.5
Localisation Angle	Area of influence around a given model grid point	Reduce spurious correlations	Reduce information updating grid point	15°	10°
Change Parameters	Allowed change at update for each variable	Allow more model freedom	Ensemble collapse and reduced stability	TBC	TBC

Table 1: Tuned AENEAS parameters. FS = baseline (Factory Settings); Opt = optimised values; TBC = To Be Completed.

## 5. Results

### Global Behaviour:

- Opt shows more physically realistic global structure with less influence from sporadic observations.
- Opt has wider global ensemble spread without runaway inflation, improves responsiveness to changing conditions.

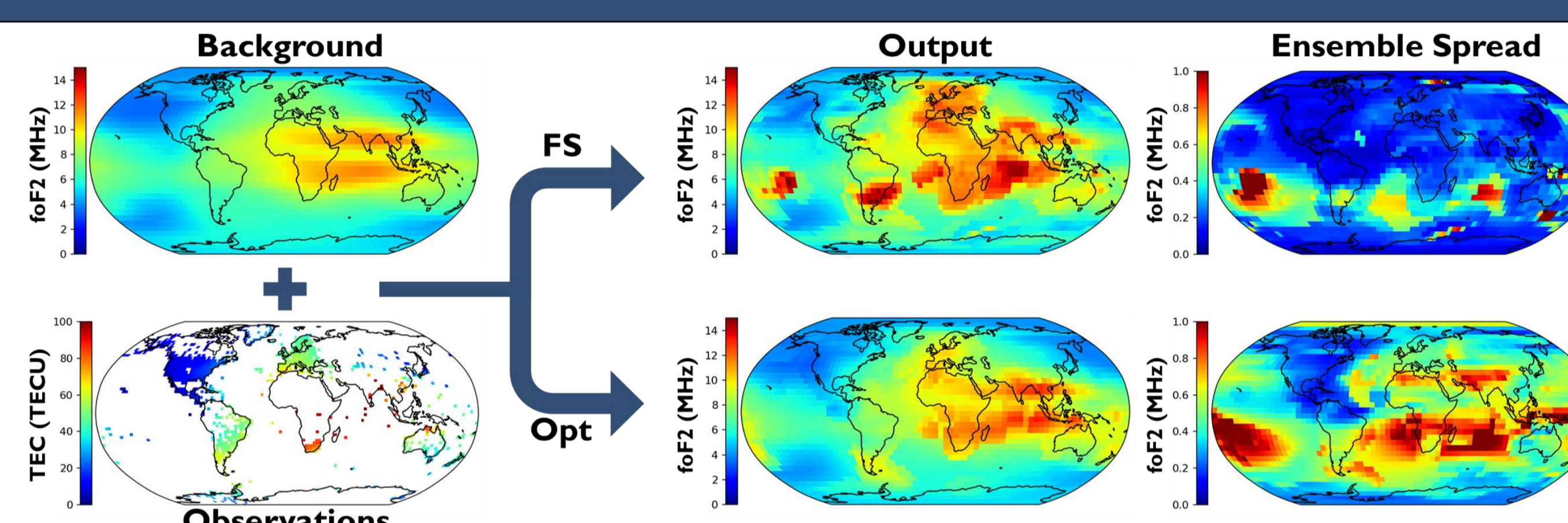


Figure 6: Global maps (12:00 UT, 8 Feb 2025) of background foF2 and GNSS TEC observations assimilated in AENEAS, comparing factory settings (FS) and optimised (Opt) outputs.

### Statistical Performance:

% $\Delta$ (Opt vs FS)	RMSE	MAE	R	$\chi^2$
foF2	+ 17.91	+ 18.54	+ 06.74	+ 39.30
hmF2	+ 26.24	+ 21.43	+ 55.98	+ 39.17

Table 2: Percentage change in performance metrics for Feb 8, 2025; positive values indicate improved performance in the Opt configuration. Metrics: root mean square error (RMSE), mean absolute error (MAE), chi-squared ( $\chi^2$ ; representing ensemble spread), and Pearson correlation coefficient (R).

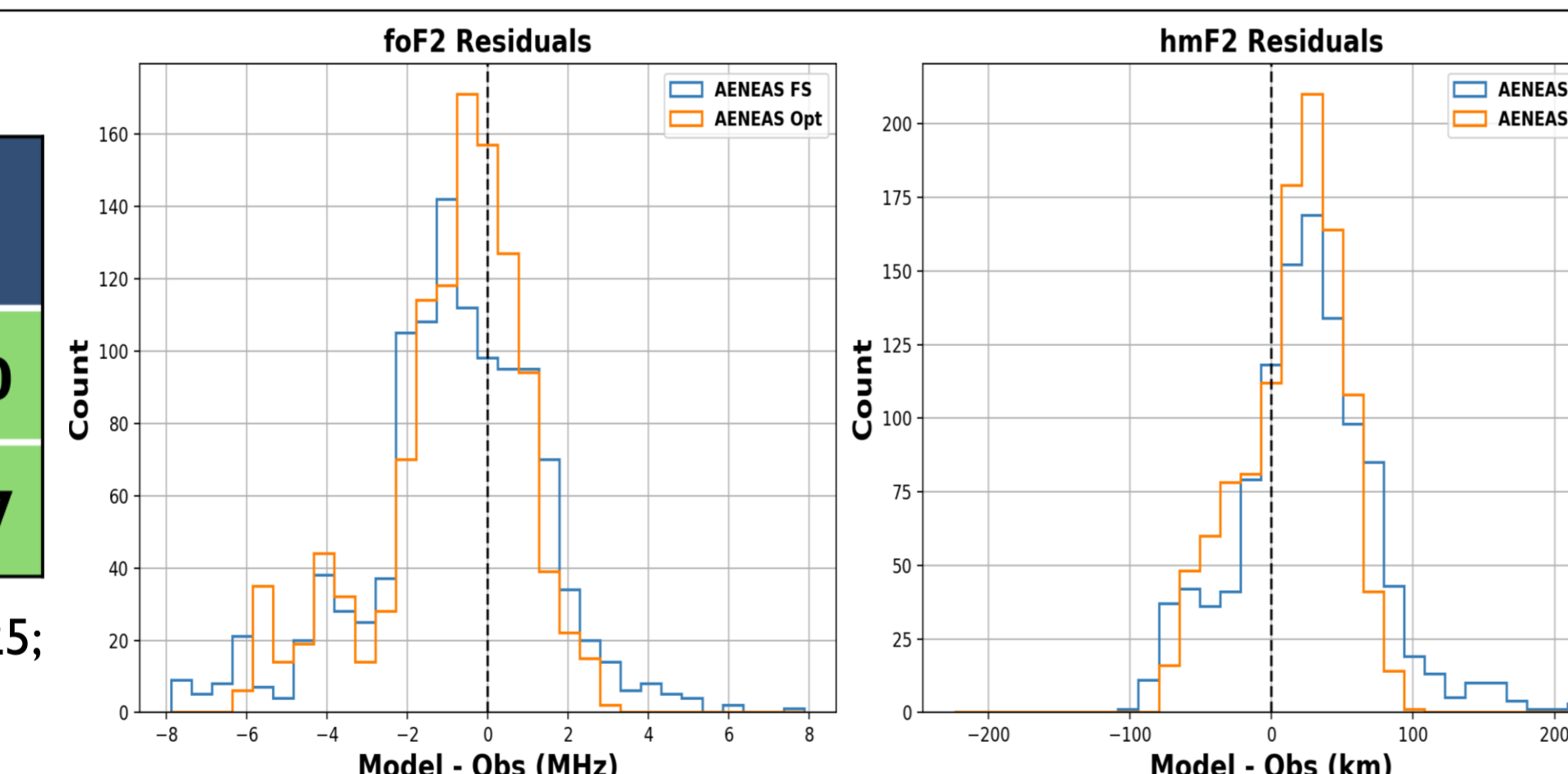


Figure 7: foF2 and hmF2 residual distributions comparing FS and Opt configurations.

### Station-level Performance & Summary

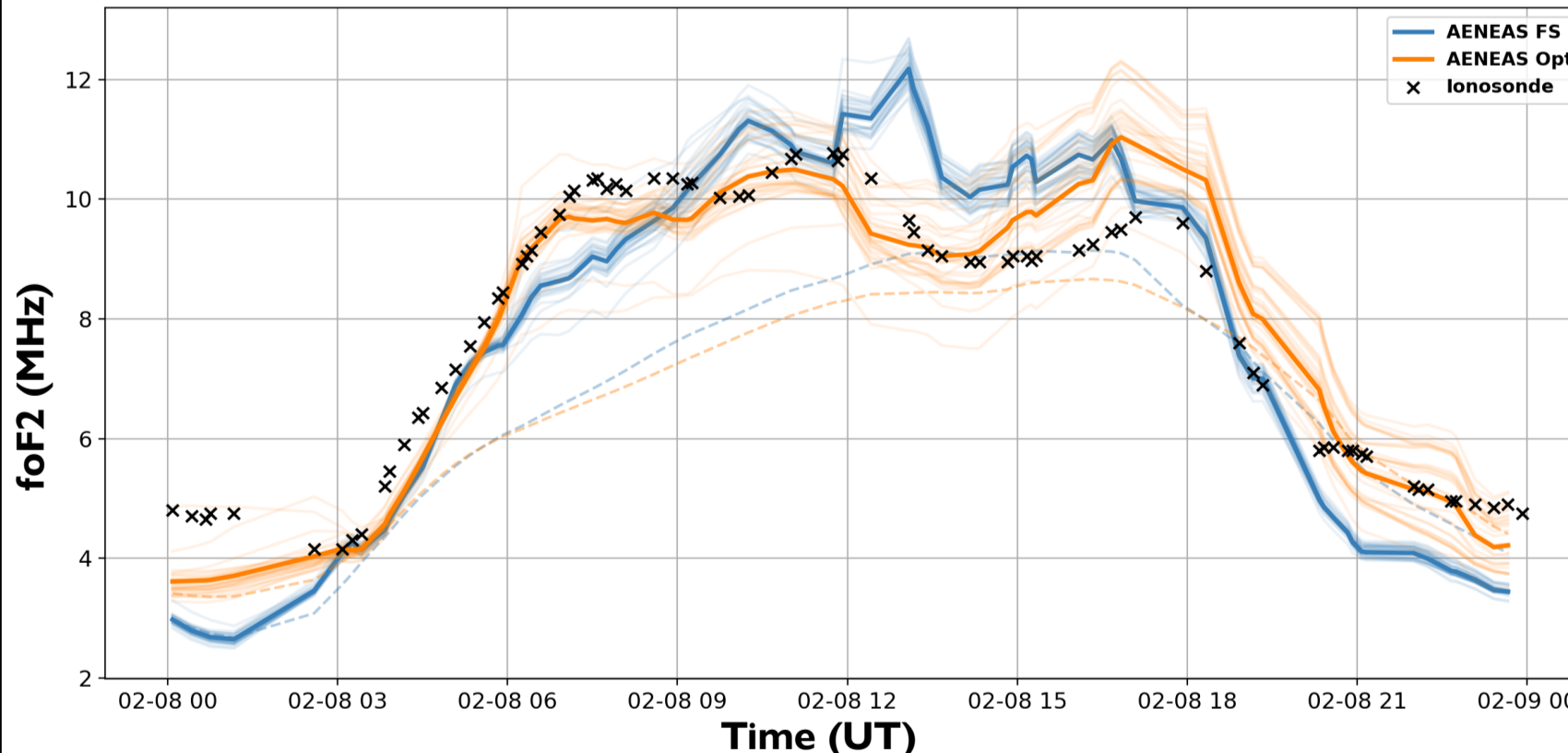


Figure 8: foF2 at Grahamstown (8 Feb 2025); dashed lines show AENEAS without DA.

- Opt improves performance across all statistical metrics for both foF2 and hmF2.
- Opt reduces the influence of assimilated data, leading to less erratic behaviour and fewer outliers.
- Optimisation increases ensemble spread without runaway inflation, enables model to better explore various I-T states.
- Limitations remain with **TEC-only assimilation**, particularly in data-sparse regions and for hmF2, due to limited vertical sensitivity.

## 6. Conclusions & Future Work

**Optimisation improved model performance** by increasing ensemble spread, better balancing the background model with assimilated data, and enhancing understanding of tuning parameters.

The resulting optimised configuration will be applied to a **geomagnetically disturbed period in July 2017** to assess **robustness** under storm conditions and **benchmark** performance against other models.

Future work includes a complete **global validation of AENEAS** across the full range of solar and geomagnetic conditions, alongside improvements to ensemble generation and the assimilation of additional data sources.

## References & Acknowledgements

- Elvidge, S. and Angling, M.J. (2019). Using the local ensemble transform kalman filter for upper atmospheric modelling. *Journal of Space Weather and Space Climate*, 9:A30.
- Coster, A. (2025). Data from the CEDAR Madrigal database. MIT/Haystack Observatory. Available at: <http://millstonehill.haystack.mit.edu/list/> [Accessed: 6 April 2026].
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