TIme-Variable Ionospheric Electric Field (TiVIE) Model: Capturing Solar Wind-Magnetosphere-Ionosphere Variability

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1 Introduction

The morphology of the ionospheric electric field in the solar wind-magnetosphere-ionosphere system has traditionally been described based on the speed of the solar wind, interplanetary magnetic field (IMF) strength, and orientation. However, existing models often average over a single timescale, neglecting the system's dynamics that vary on multiple timescales from minutes to hours. This limitation is particularly problematic on the night side of the planet, where convection is influenced by both dayside and magnetotail reconnection.

To address these limitations, the Time-Variable Ionospheric Electric field (TiVIE) model has been developed. This model incorporates novel parameterizations that capture the major sources of time-variability in the coupled solar wind-magnetosphere-ionosphere system. It improves upon existing models by considering the time-dependence of the system and utilizes data from the Super Dual Auroral Radar Network (SuperDARN) for large-scale observations of the ionospheric electric field.

The TiVIE model accounts for three significant sources of variability: solar wind conditions, substorm onsets, and geomagnetic storms. By incorporating these factors, the model aims to better represent the ionospheric electric field and provide a more accurate understanding of the system's behaviour.

We present the key features and capabilities of the TiVIE model version 1.0, compare it with existing models and observations, and discuss its potential applications in large-scale models such as whole atmosphere models or space weather models. The TiVIE model offers a significant advancement in capturing the time-dependent behavior of the solar wind-magnetosphere-ionosphere system, providing valuable insights into the variability of the ionospheric electric field.

2 SuperDARN data

TiVIE uses data from the Super Dual Auroral Radar Network in the northern hemisphere. This is a network of ground-based HF radars which can measure ionospheric flows. We use line-of-sight flow data together with a spherical harmonic fitting technique which allows us to make convection maps, gridded into equal-area magnetic latitude and magnetic local time.

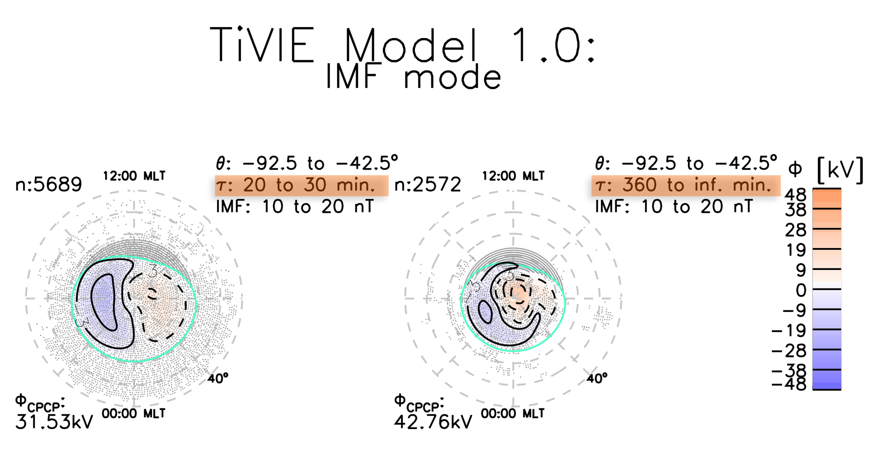
We use data with a 2-minute temporal cadence. The SuperDARN data uses a standard operating mode (i.e. "Common Time" radar data) and we apply a range limit criteria to include observations within specific slant ranges (800 km to 2000 km). This helps reduce contamination by lower-velocity E region echoes and minimizes geolocation inaccuracies.

3 TiVIE Model

The TIme-Variable Ionospheric Electric field (TiVIE) model is designed to capture the **time-dependent behavior** of the solar wind-magnetosphere-ionosphere system. It incorporates data from the Super Dual Auroral Radar Network (SuperDARN) and considers three major sources of variability: **solar wind conditions, substorm onsets, and geomagnetic storms**. TiVIE provides **improved parameterizations for time-variability** compared to existing models.

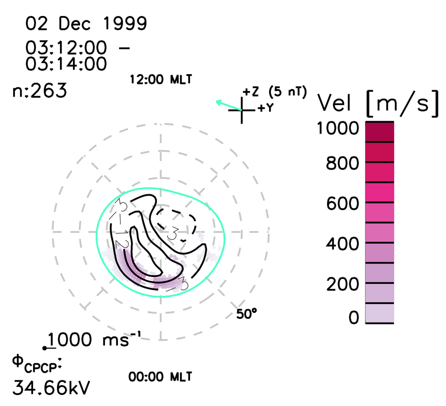
4 TiVIE Mode 1: IMF conditions

- Parameterised by:
  - **IMF magnitude** (0 to 3 nT; 3 to 5 nT; 5 to 10 nT and 10 to 20 nT),
  - **clock angle**, θ, (16×50° wide bins, overlapping by 22.5° each),
  - and **steadiness timescale**, τ (20 to 30; 30 to 40; 40 to 60; 60 to 90; 120 to 18; 180 to 240; 240 to 360 and > 360 minutes).
- τ reflects for how long the IMF has been steadily pointing in the same direction at the same IMF magnitude and has to be satisfied 90% of the time.



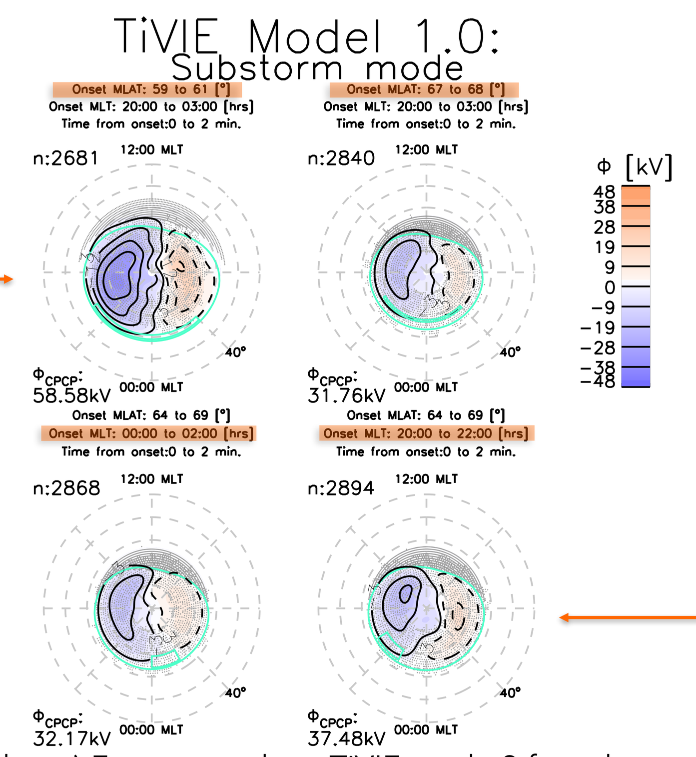
(above) Two maps show TiVIE mode 1 for northward, negative IMF B_Y. The black lines show the electric equipotentials and the turquoise line shows the Heppner-Maynard boundary. The left shows a short τ and the right shows a long τ.

τ influences the morphology:
The dusk cell extends across the nightside (Figure above on the right).
This is consistent with findings by Grocott+ (2007) and is also shown by the convection map (right), which shows an example of this convection morphology from the SuperDARN data archives.



5 TiVIE Mode 2: Substorms

- Similar to Grocott+ (2017) we create a superposed epoch analysis which is parameterised by substorm onset time and location.
- We try two different parameterisations:
  - 1° latitude bins from 59° to 71° with MLT 20:00 to 03:00 hrs
  - 64 to 69° magnetic latitude with MLT 00:00 - 02:00 or 20:00 - 22:00 hrs

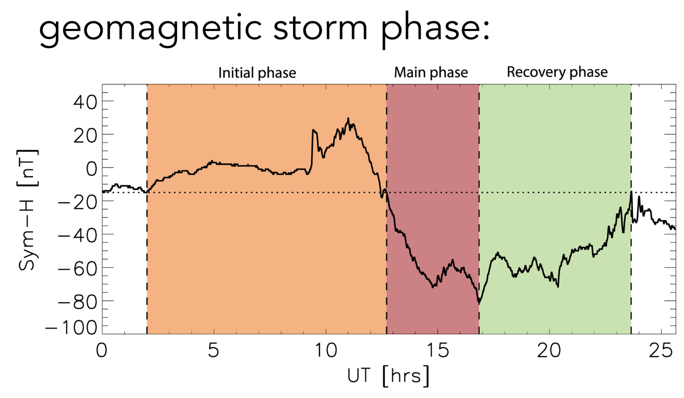


(above) Four maps show TiVIE mode 2 for substorm onset. Different onset locations are highlighted by the turquouise segments.

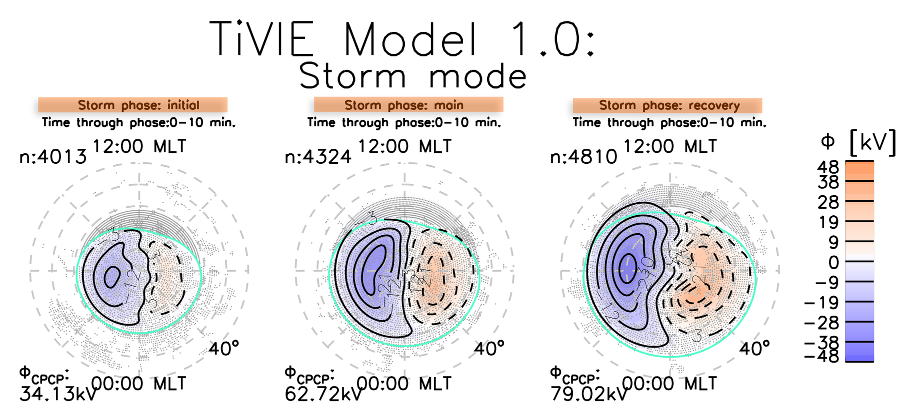
Onset location influences the morphology:
Flow reversal location, Heppner-Maynard boundary and transpolar voltage, Φ_{CPCP}, are affected.
This is consistent with previous findings from Grocott+ (2010), who also subsampled the substorms by IMF B_Y. Including IMF B_Y increases dusk-dawn asymmetries we see in the bottom row. Our onset location (bottom right) does not fully align with the convection throat, which is likely due to small differences in the processing methods.

6 TiVIE Mode 3: Geomagnetic storms

- Similar to Walach+ (2019, 2021a), we parameterise by geomagnetic storm phase:



(above) Initial phase, main phase and recovery phase are chosen by Sym-H index, based on a threshold of -80 nT for main phases (after Hutchinson+ 2011, Walach+, 2019)



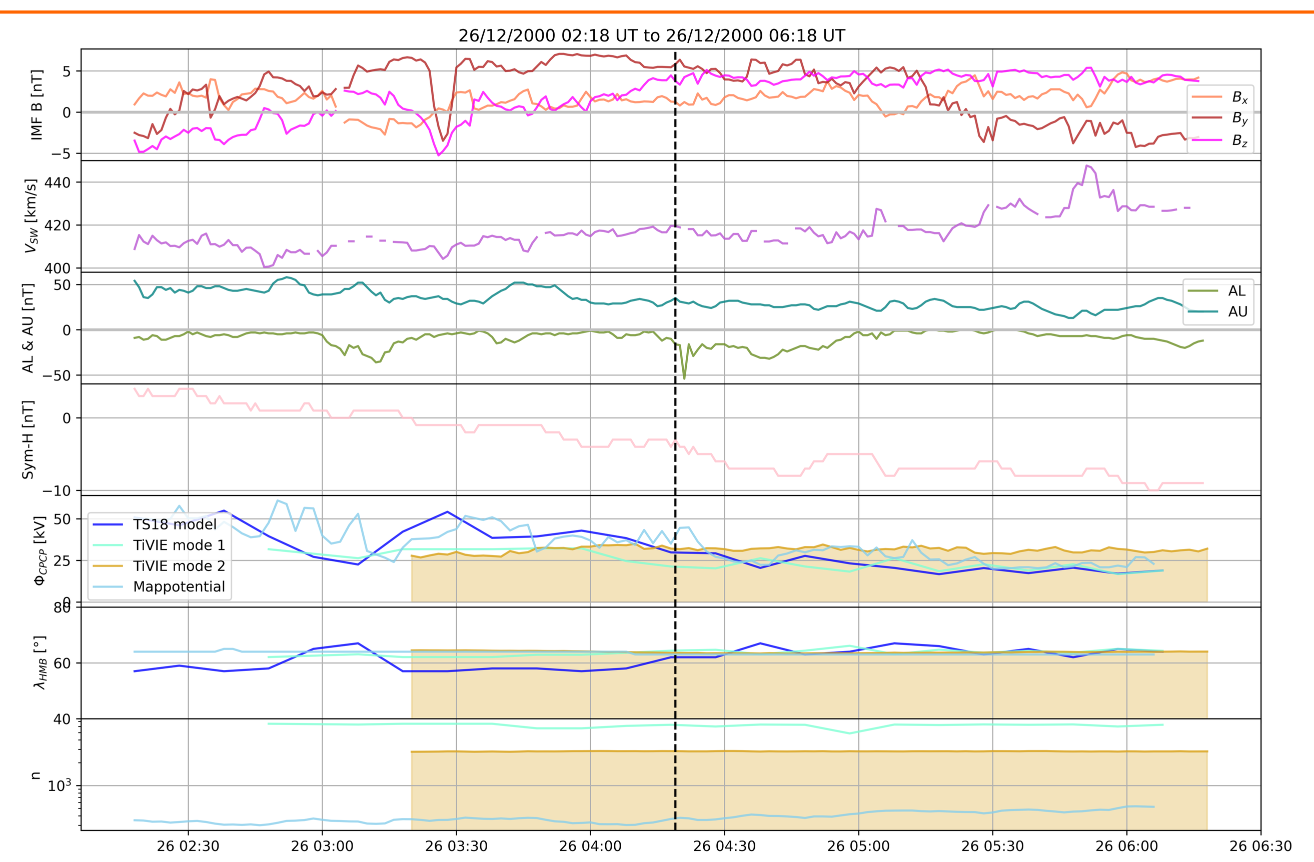
(above) Three maps show TiVIE mode 3 for the start of each geomagnetic storm phase. The electric field changes in response to the geomagnetic storm, becoming stronger as the storm progresses through the main and into the recovery phase.

Geomagnetic storm phases influence the morphology:
Heppner-Maynard boundary, Φ_{CPCP}, and dayside convection throat respond to storm phases.

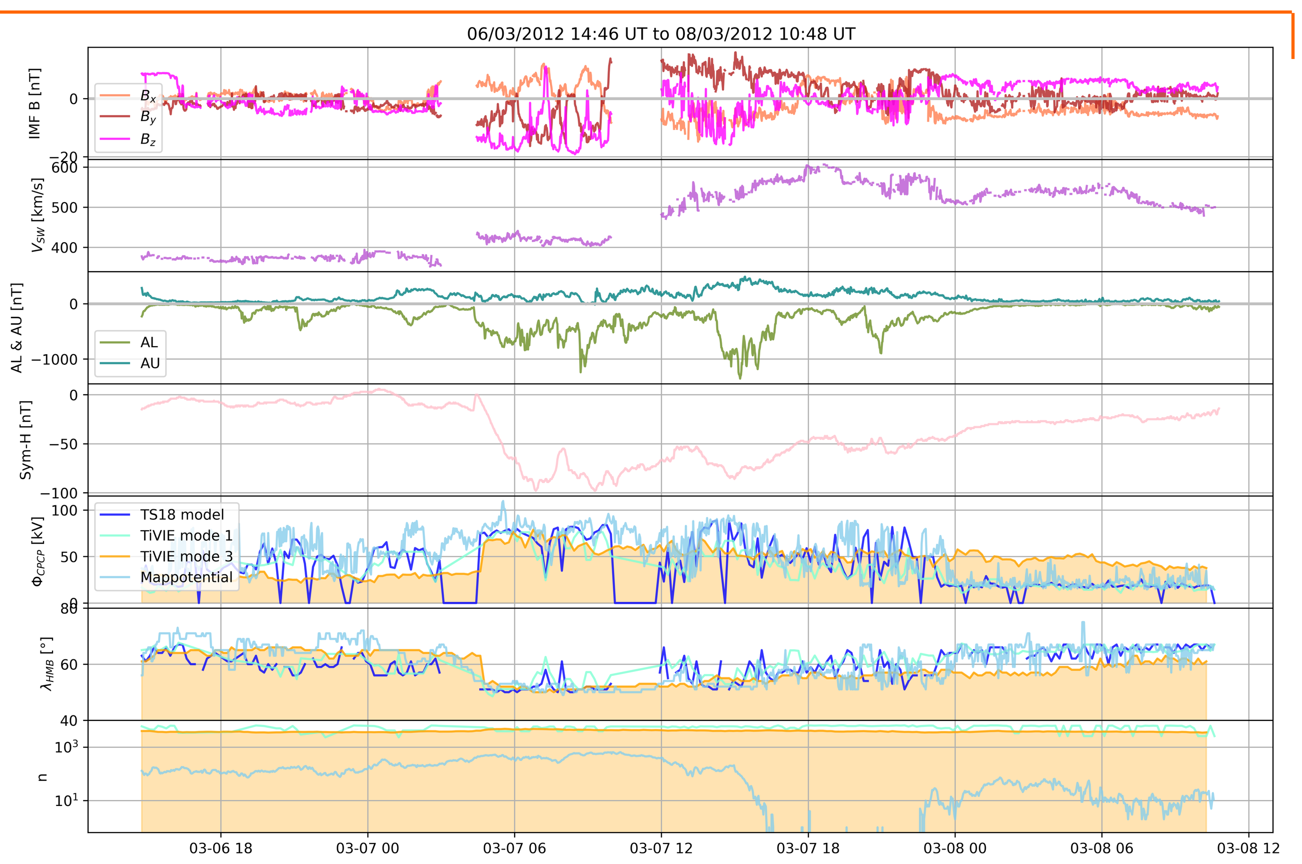
This is consistent with previous findings from Walach+ (2019 and 2021a). Walach+ (2019) found that the Heppner-Maynard boundary expands to as latitudes as low as 40° and Φ_{CPCP} reaches up to 140 kV during the main phase of geomagnetic storms. Walach+ (2021a) found that the dayside convection throat moves from the mid-morning sector to be more sun-aligned.

6 TiVIE in action

- Two examples comparing TiVIE mode 1 and 2 for an isolated substorm (left) and mode 1 and 3 for a geomagnetic storm (right)
- Mode 3 overcomes issues of data gaps in solar wind data.
- Further examples of TiVIE mode 3 is shown by Orr+ (2023): This study compared TiVIE mode 3 to other popular electric field models (Heelis+ (1982, 1990); Weimer (2005); Thomas & Shepherd (2018)).
- A key finding from Orr+ (2013) was that models solely driven by solar wind conditions can expand too quickly during geomagnetic storms.



(above) Example substorm (black dashed vertical line shows onset), showing solar wind conditions, geomagnetic indices (AL, AU & Sym-H). The bottom three panels show Φ_{CPCP}, the Heppner-Maynard boundary and the number of datapoints per map, n for the Thomas and Shepherd (2018) model (royal blue), TiVIE modes 1 (turquoise) and 2 (yellow) and the SuperDARN map archive, labelled as Mappotential (light blue).



(above) Example geomagnetic storm. Panels are showing the same parameters as on the left but bottom four panels show TiVIE mode 3 in orange.
Advantages of TiVIE:
Time-history of the event is captured; No susceptibility to data gaps; smooth transition between phases or different solar wind conditions

Summary

One of the key advantages of TiVIE is its flexibility. It allows users to run different TiVIE modes individually or in combination, providing customization options based on solar wind conditions such as speed, IMF strength, or clock angle limits. This flexibility enables researchers to study and analyze the behavior of the solar wind-magnetosphere-ionosphere system under various conditions.

In summary, the TiVIE model is a valuable tool for studying the time-dependent dynamics of the solar wind-magnetosphere-ionosphere system. It offers a novel parameterisations, which model the time history of the solar wind-magnetostphere-ionosphere by incorporating SuperDARN data, and provides a novel way to model the electric field's response to space weather.

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- The Radar Software Toolkit (RST) to process the SuperDARN data can be downloaded from Zenodo (DOI:10.5281/zenodo.1403226).
- Solar wind data (OMNI 1-min), Sym-H, AL and AU from NASA's SPDF Coordinated Data Analysis Web (https://cdaweb.gsfc.nasa.gov/index.html/).
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