Modeling Regional Ionospheric Electron Density

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Overview

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1. Background

- Ionosphere (~50-1,000 km above Earth’s surface)
  - Region of high electron density
  - Fluctuations affect communication, navigation, etc.
  - GPS signals attenuated, refracted, reflected

- Electron density variability
  - Solar flux, geomagnetic activity, periodic variability
  - Forcing from below? (Goncharenko et al. 2018)

- Project goal: create an empirical model for ionospheric total electron content (TEC) using geomagnetic activity, solar flux, and seasonal variation as parameters.

Credit: Rishbeth 1988

Typical Ionospheric Profile
2. Data Sources

- TEC – GNSS, provided by CEDAR Madrigal database.
  - Delay between two radio frequencies isolates TEC
  - Measured in TEC units (1 TECU = 10^6 electrons/m^2)
  - Available in 1° x 1° bins with 5 min temporal resolution since 2000

![Binned vTEC, 15 March 2013, 00:00:00](image)
2. Data Sources

• Solar Flux and delays
  • 10.7cm radio flux (f10.7) – CEDAR Madrigal Database
  • Extreme Ultraviolet flux (EUV) – TIMED Solar Extreme Ultraviolet Experiment (SEE)

• Geomagnetic Activity
  • Ap3 (3-hour Ap index), Kp (logarithmic), and delays – CEDAR Madrigal Database
3. Dealing with Data Quality Problems

- Sidereal motion of satellites causes periodic “streaks” in TEC data plot
  - More severe at solar minimum (absolute error remains relatively the same)
- Regions of low GPS coverage offer less data
- Goal: remove “streaks” while preserving reliable TEC variability
3. Dealing with Data Quality Problems

- Hampel filter
  - Vertical (13 point window, 1σ criterion)
  - Horizontal (3 point window, 3σ criterion)
- Cubic spline interpolant with low tolerance
- Iterative model-building - removal of points with:
  1. % data-model beyond 2σ of the mean
  2. Solar flux and delays < 0.007 W/m²
  3. Ap3 and delays < 80 sfu
4. Input Parameters: Solar Flux

• Indices available for use: EUV, f10.7
  • f10.7 – captures last solar cycle of data well according to Mukhtarov et al. (2013)
  • EUV – more comprehensive, able to identify smaller-scale disturbances

• Modulation by annual, semiannual, four-monthly, and three-monthly terms.

• Different delays investigated – not a moving 81-day average of solar flux

• Sample: 45LAT, 0LON
4. Input Parameters: Geomagnetic Index

- Several available indices – Ap3, Kp, Dst
- Longer-term delays statistically significant for general model – 3 hour, 24 hour, 48 hour, 72 hour
- Sample: 45LAT, 0LON
4. Input Parameters: Solar Zenith Angle

- Potential to be used in place of annual periodic fluctuation/modulation
- Less easily implemented into the model, no improvement in performance.
- Convenience of use
- Sample: 45LAT, 0LON
4. Input Parameters: Final Selection

- EUV flux (quadratic)
- EUV delays: 1 day, 8 days, 24 days, 36 days
- Ap3 index (quadratic)
- Ap3 delays: 3 hours, 24 hours, 48 hours (quadratic), 72 hours
- Seasonal terms: annual, semiannual, four-monthly, three-monthly
- Modulation of EUV linear term by annual, semiannual, three-monthly terms
- Modulation of EUV quadratic term by all periodic terms

**Total number of predictors: 36**
5. Results and Model Performance

• Final Model: Linear Regression
  • Notable/unprecedented: developed at 45° latitude with 3° spatial resolution in longitude, 30 minute temporal resolution
  • RMS Error of 1.78 TECU for whole model at 45LAT
    • 3.387 TECU for Mukhartov et al. (2013), ~2.9 TECU for Feng et al. (2019), 3.5 TECU for Lean et al. (2016)
  • Metrics considered: MAE, MSE, RMSE, MARE, MSRE, RMSRE, MAPE, MSPE, RMSPE

![TEC data at 45LAT, 0LON, 01-Jan-2015 - 01-Jan-2016](image1)

![TEC model at 45LAT, 0LON, 01-Jan-2015 - 01-Jan-2016, v74](image2)

![TEC, 45LAT, 0LON, MAPE, Version74](image3)

![TEC, 45LAT, 0LON, RMSE, Version74](image4)

![TEC, 45LAT, 0LON, RMSPE, Version74](image5)
5. Results and Model Performance

- Solar flux dependence
  - Increase in error associated with model at high solar flux values
  - Better model performance for moderate solar flux values
6. Future Work

• Expansion of model to other latitudes with $3^\circ \times 3^\circ$ spatial resolution.

• Expansion of model to longer time period
  • GNSS TEC available since 2000
  • Geomagnetic/Solar Flux Indices available since 1963
  • EUV only available from TIMED SEE since 2002
  • Possible to expand EUV coverage to 2000 using SOLAR2000 model

• Investigation of additional drivers/independent variables

• Identification of anomalies using final model
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8. References


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