A high latitude topside electron density representation for the Empirical Canadian High Arctic Ionospheric Model (E-CHAIM)

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Outline

- Introduce E-CHAIM.
- Discuss the data used in fitting the new model.
- Discuss current topside standards.
- Present the E-CHAIM topside parameterization.
- Discuss the fitting performance of the model.
- Discuss the predictive performance of the model.
- Examine an example during a strong storm.

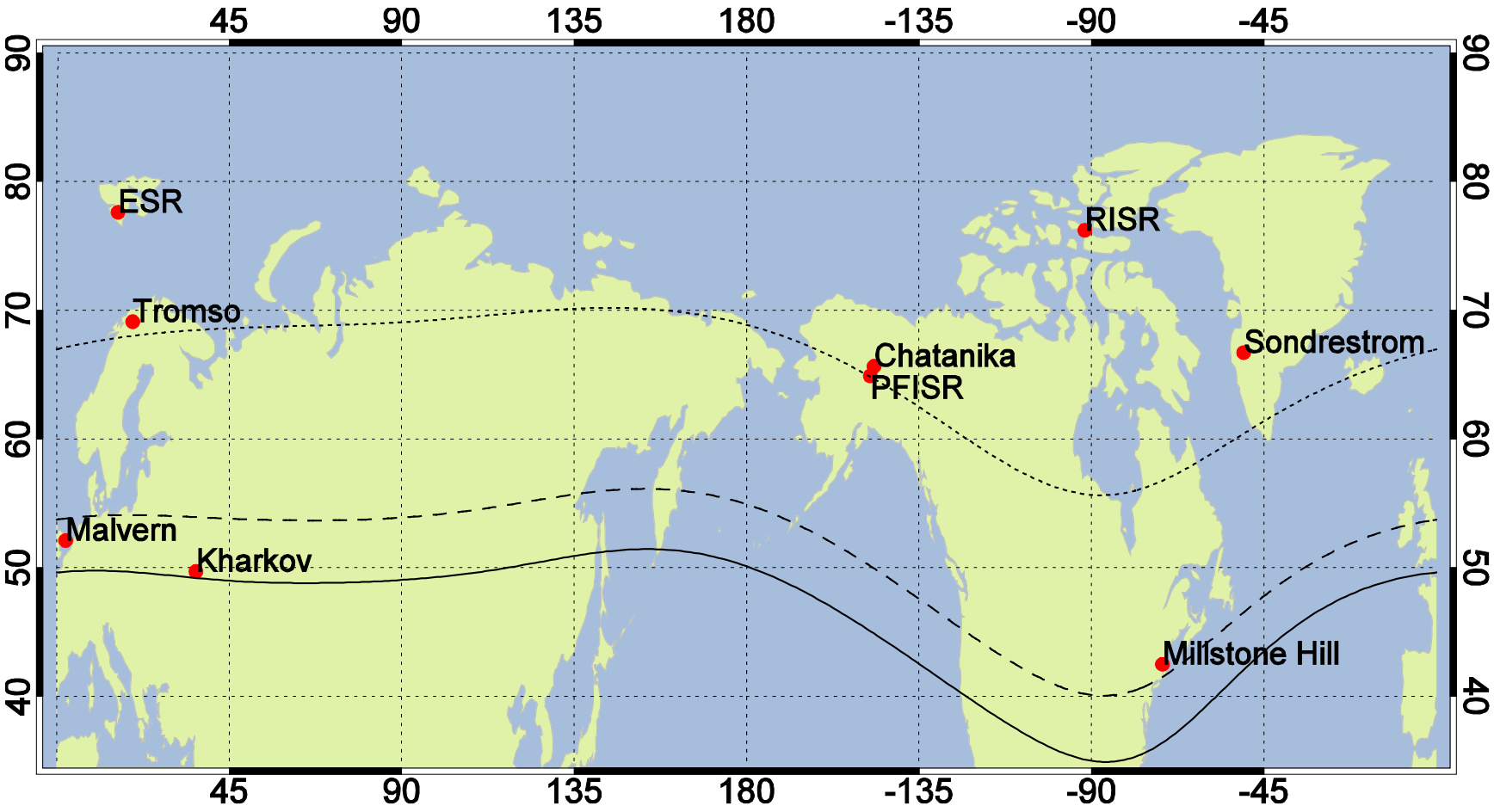
E-CHAIM

- An empirical model of high latitude (MLAT > 50N) electron density.
- It is designed as a replacement for the use of the IRI at high latitudes.
- hmF2, NmF2, NmF2 Storm, Topside, and error models are now complete.
- The model will be made available at http://chain.physics.unb.ca once a distribution is completed. Until then, please send requests by email to david.themens@unb.ca

Dataset: Incoherent Scatter Radar

- Data is gathered from nine ISRs at high or upper-mid latitudes.
- Data from beam elevations above 45 degrees are gathered in altitude bins on 15 minute intervals.
- PDFs are generated for each bin and are fitted to a Gaussian to determine the density and error for each profile point.
- Overall, 960,450 ISR profiles are used for model fitting.

ISR Locations



Dataset: Radio Occultation

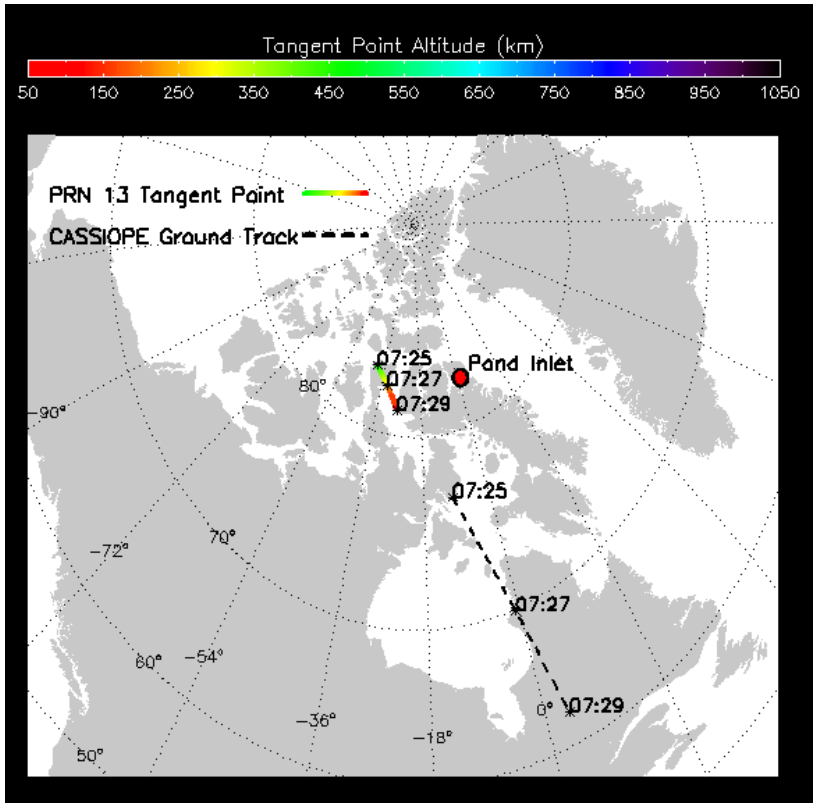
- CHAMP, GRACE, and COSMIC GPS Radio Occultation electron density profiles.
- Gathered all profiles from above 45N geomagnetic latitude (736,828 profiles).
- Profiles with negative values anywhere above 100km are discarded.
- Noise-dominant profiles are identified and removed by evaluating RMS errors with respect to a fitted vary-Chap profile.
- Profiles with multiple maxima are removed.

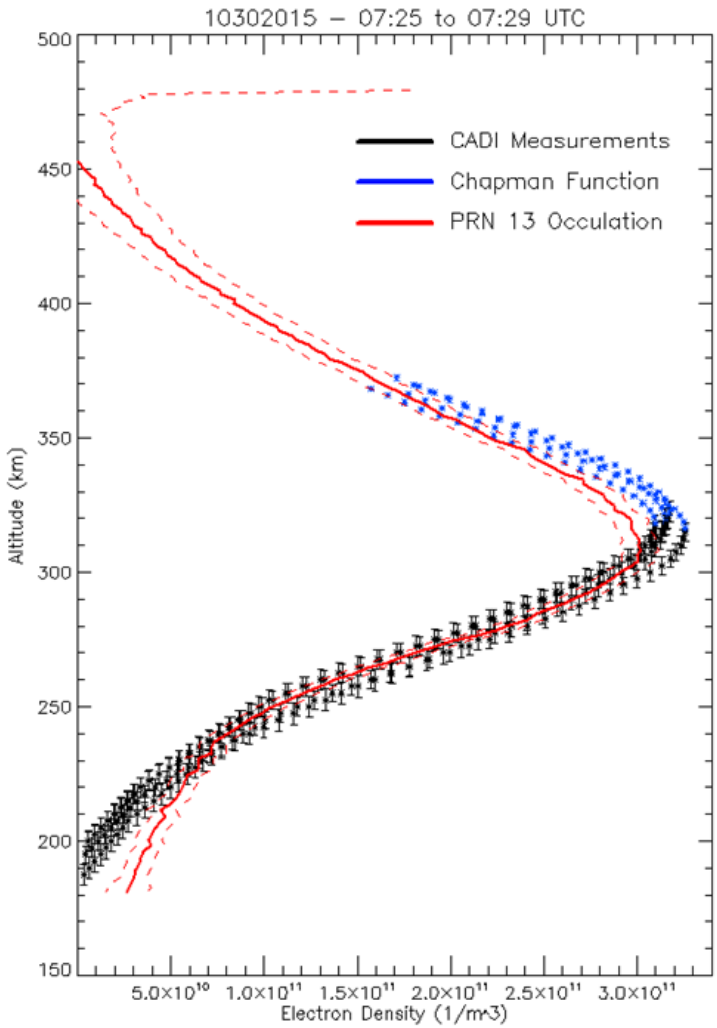
Dataset: Topside Sounder

- Data are gathered from the IK-19, Alouette (1a, 1b, 1c, and 2), and ISIS (1 and 2) topside sounder missions.
- All data above 45N geomagnetic latitude are included (76,812 profiles).
- Only data with quality control indices equal to or greater than five used.

Validation: e-POP Radio Occultation Data

- 146 Profiles available since 2013.
- Elliptical polar orbit with inclination of 81 degrees.





NeQuick Topside Model

- The current standard for global topside specification.
- Adopted as the default topside in the International Reference Ionosphere (IRI).
- Shown to exhibit significant errors at high latitudes, particularly in representing the topside thickness (Themens et al. 2014 and 2016; Bjoland et al. 2016).

NeQuick continued…

$$N(h) = \frac{4N_{max}}{(1+\exp(z))^2}\exp(z)$$

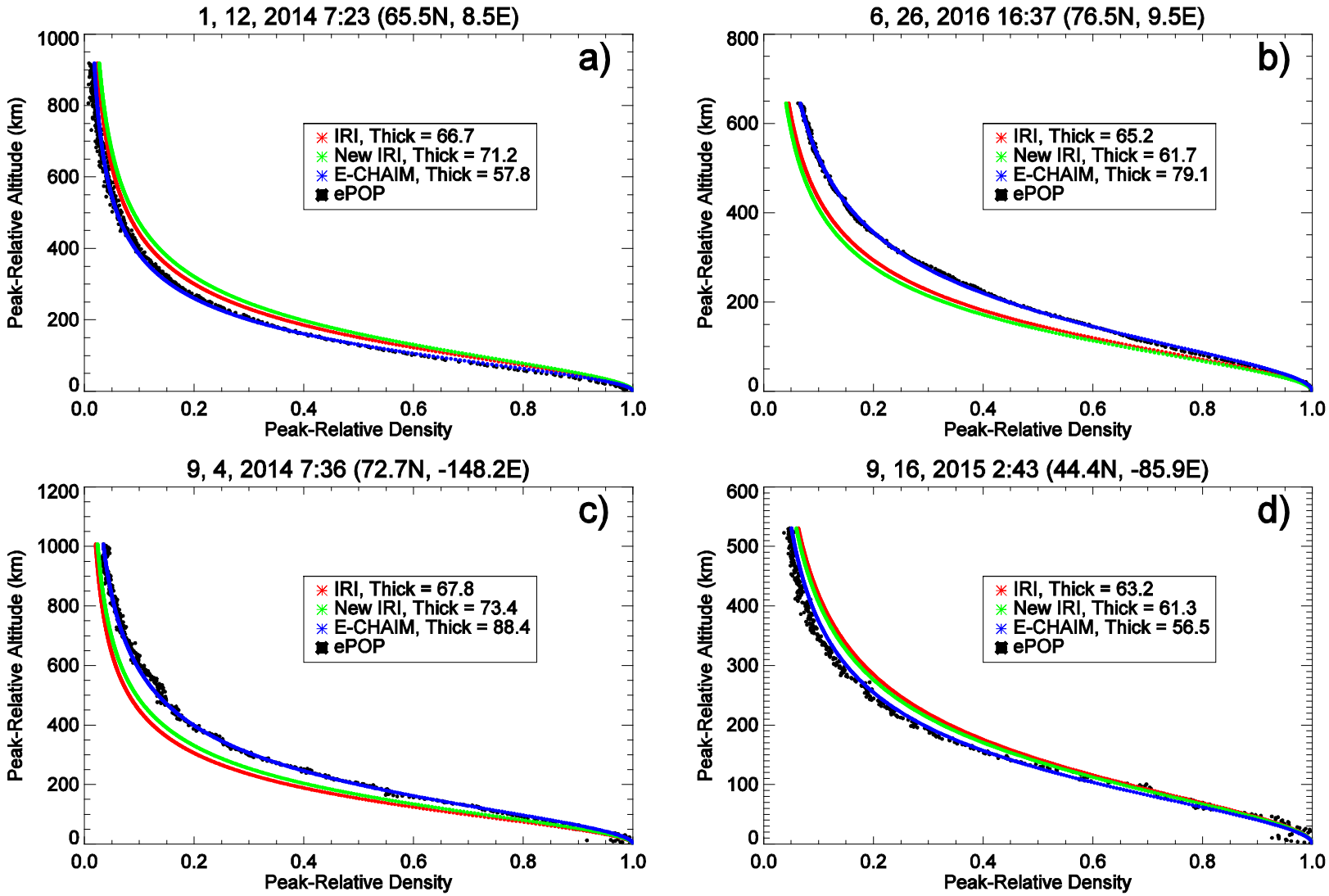
$$z = \frac{h - hmax}{H}$$

$$H = H_0\left[1 + \frac{rg(h - h_mF2)}{rH_0 + g(h - h_mF2)}\right]$$

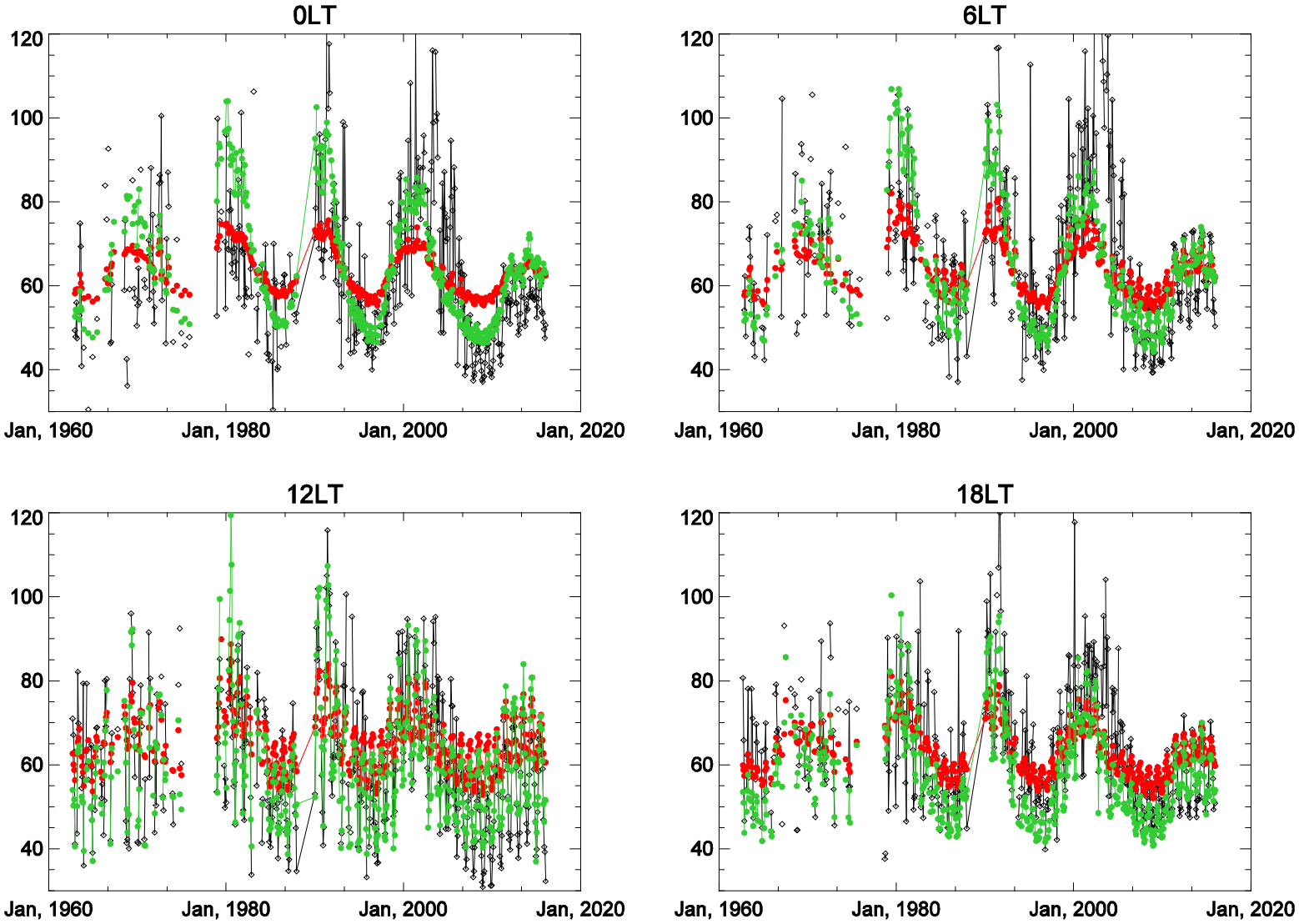
$$H_0 = k \cdot B2Bot$$

$$k = 3.22 - 0.0538foF2 - 0.00664hmF2 + 0.113\frac{hmF2}{B2_{Bot}} + 0.00257R12$$

Example profiles



IRI Performance



Model Parameterization

$$H_0 = G + \sum_{l=0}^{L} \sum_{m=0}^{\min(l,M)} \left[A_{lm} \cos\left(\frac{\pi m}{180} MLT\right) + B_{lm} \sin\left(\frac{\pi m}{180} MLT\right)\right] P_{lm}(\eta)$$

$$\eta = \cos\left((90 - \varphi)\frac{\pi}{45}\right) \qquad L = 4, \mathrm{M} = 4$$

$$A_{lm}, B_{lm} = (\gamma_{lm} F_1 + \delta_{lm} F_2) \cdot sin^2\left(\frac{\pi \cdot DoY}{365.25}\right) + (C_{lm} F_1 + D_{lm} F_2)$$

$$C_{lm}, D_{lm} = \sum_{c=1}^{4} \alpha_{lm}^{c} \cos\left(\frac{2\pi c \cdot DoY}{365.25}\right) + \beta_{lm}^{c} \sin\left(\frac{2\pi c \cdot DoY}{365.25}\right)$$

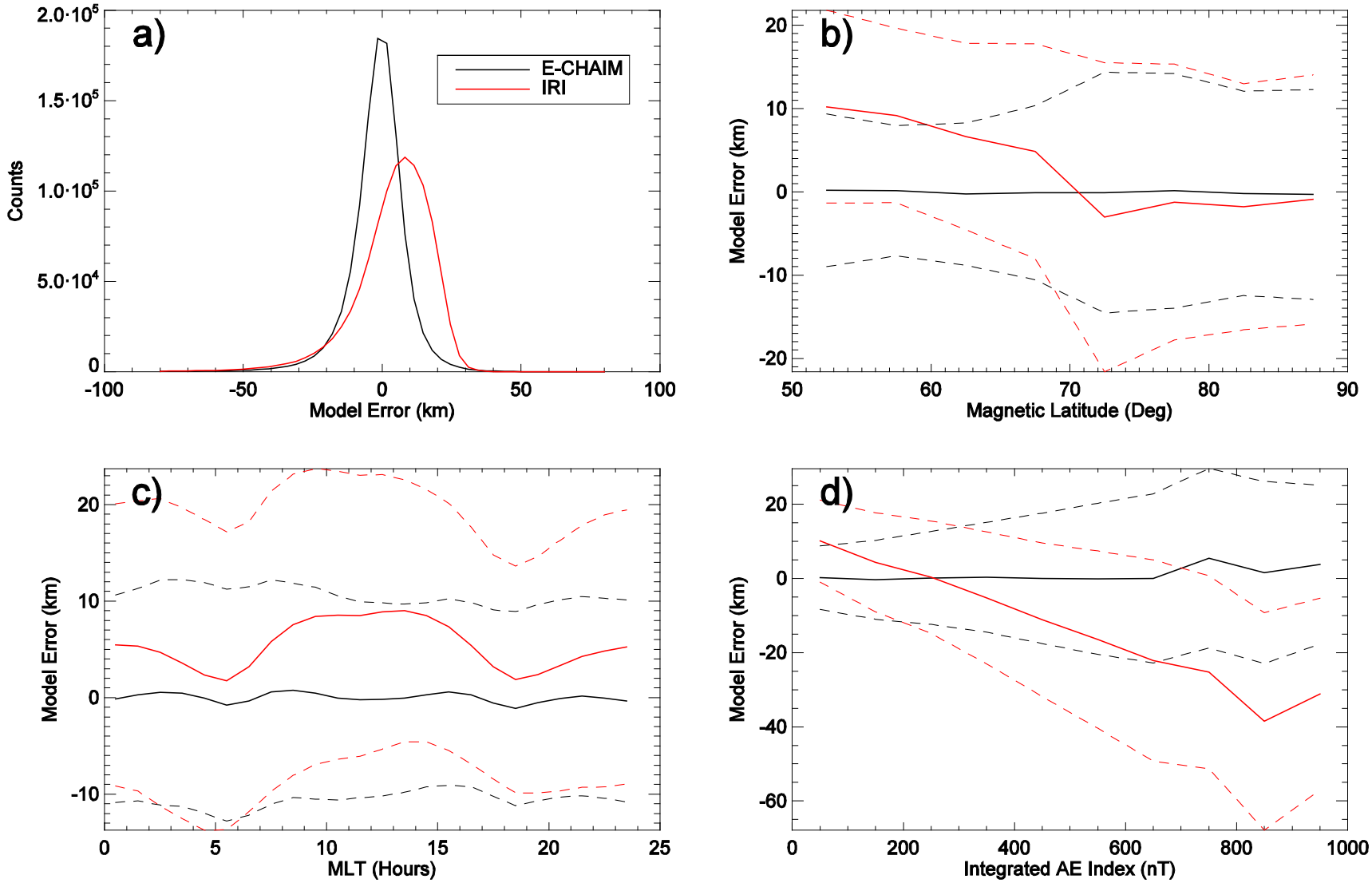
$$\mathrm{G} = F10.7 \cdot (a_1 \cos(\chi) + a_2 \sin(\chi)) + \sqrt{F10.7} \cdot (a_3 \cos(\chi) + a_4 \sin(\chi)) + IG \cdot (a_5 \cos(\chi) + a_6 \sin(\chi)) + a_7 F10.7^2 \cos(\chi) + a_8 IG^2 + a_9 \cos(\chi) + a_{10} \sin(\chi) + \cos(\chi) \cdot (a_{11} \sin\theta + a_{12} \cos\theta) + a_{13} \sin\theta + a_{14} \cos\theta$$

$$F_1 = F10.7_{81} \qquad F_2 = AE'$$

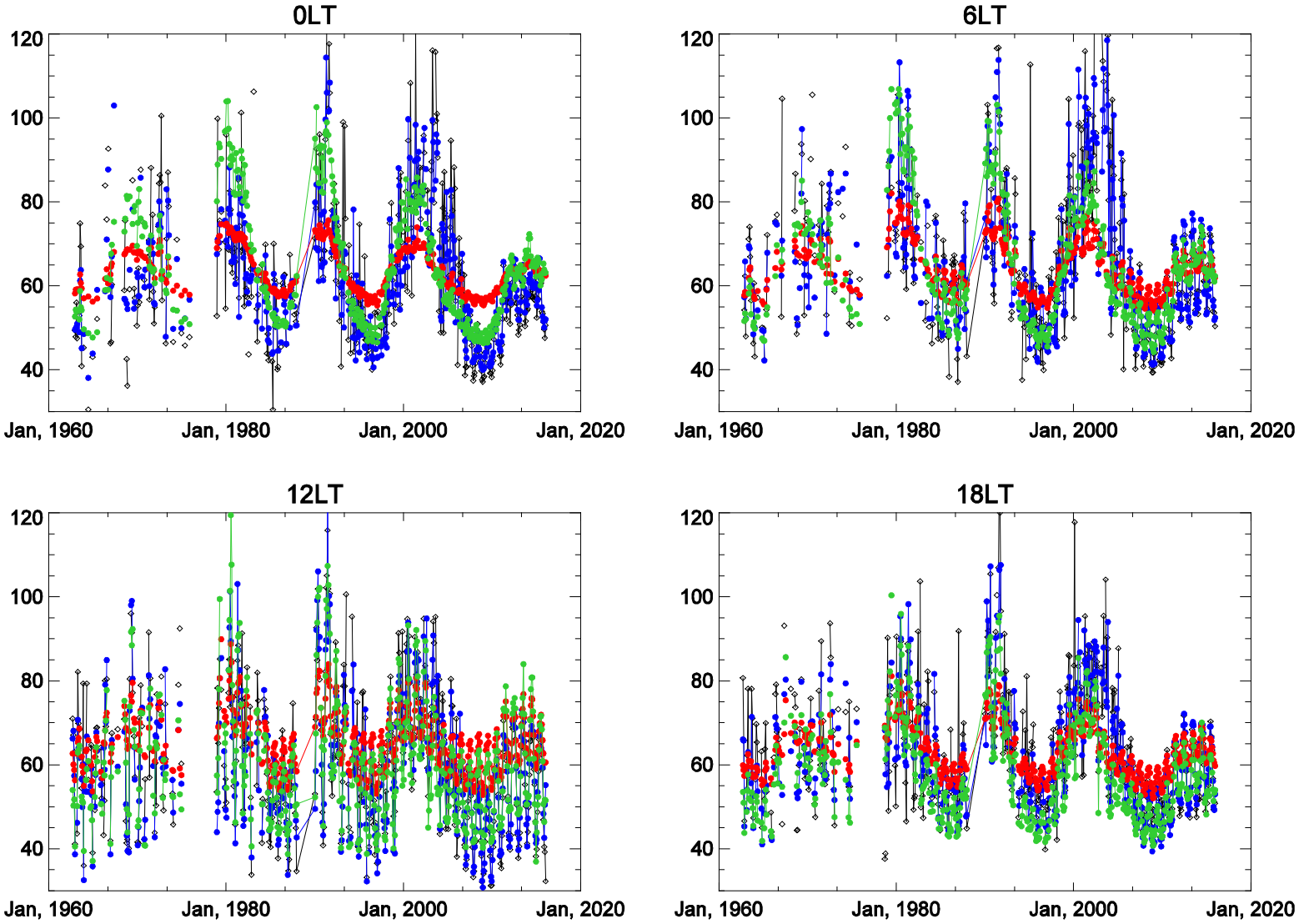
$$AE' = (1 - \tau)[AE_0 + \tau \cdot AE_1 + \tau^2 \cdot AE_2 + \cdots]$$

$$\tau = 0.95$$

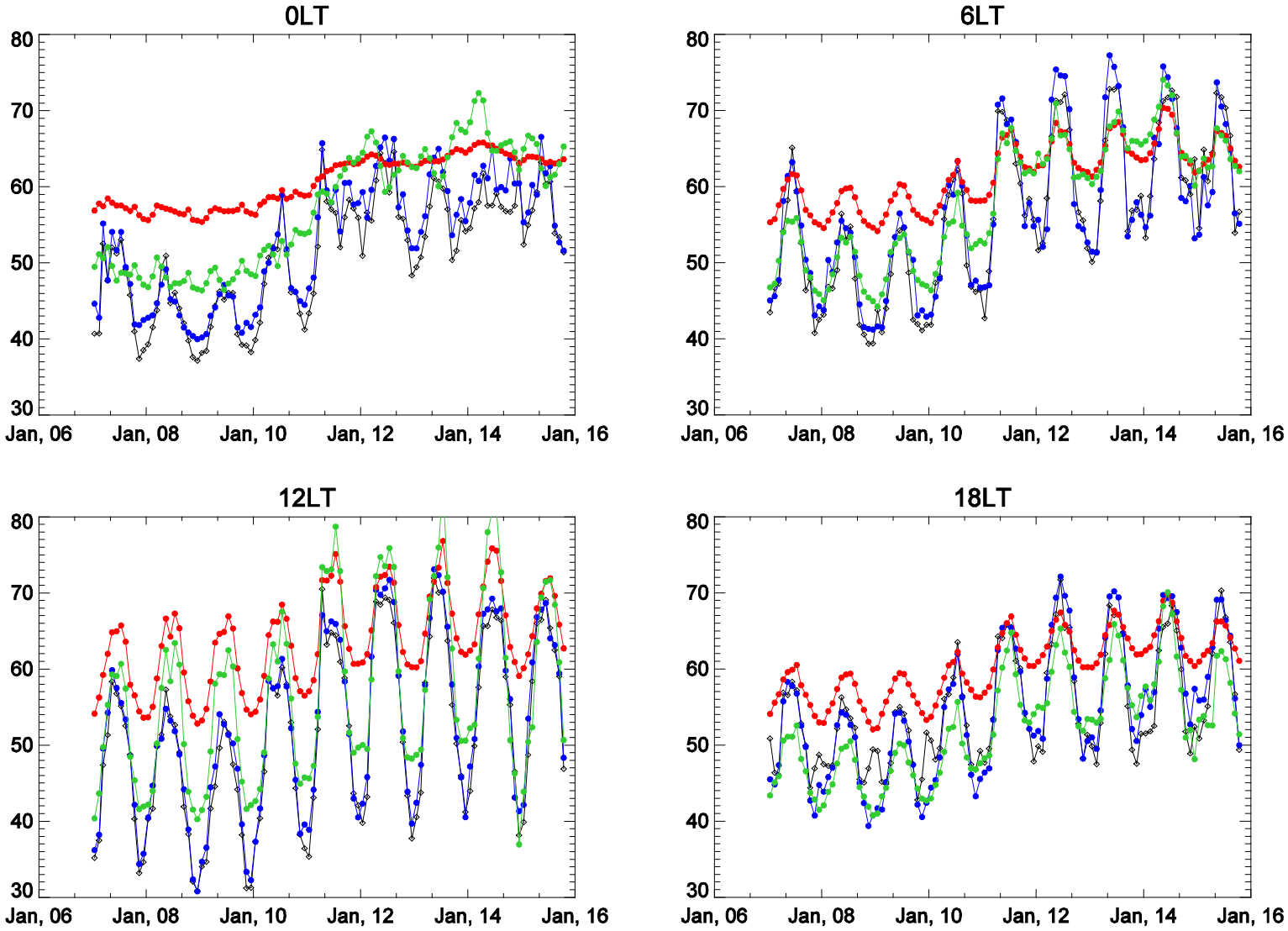
Fitting Performance vs. IRI



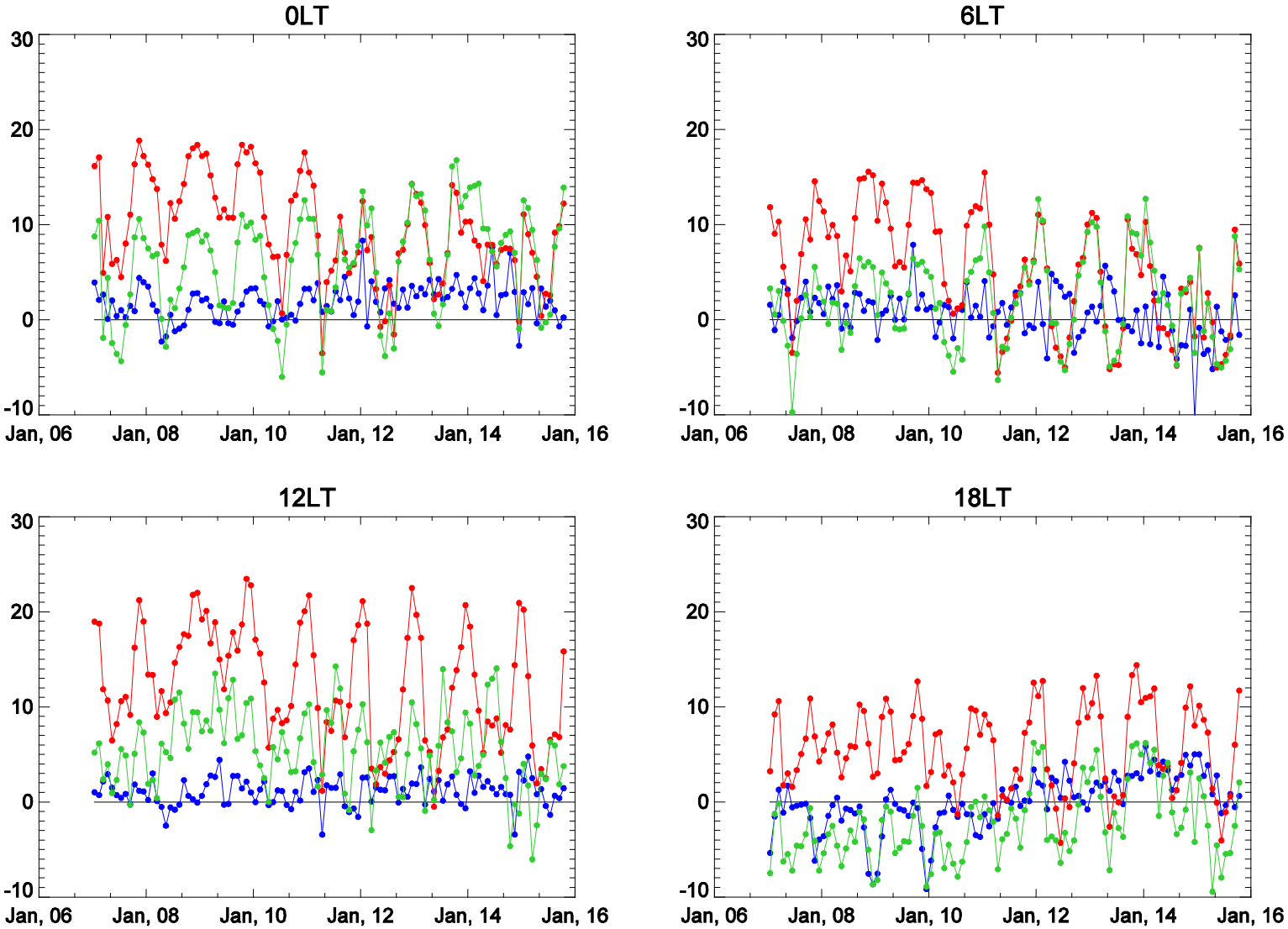
Fitting Performance vs. IRI



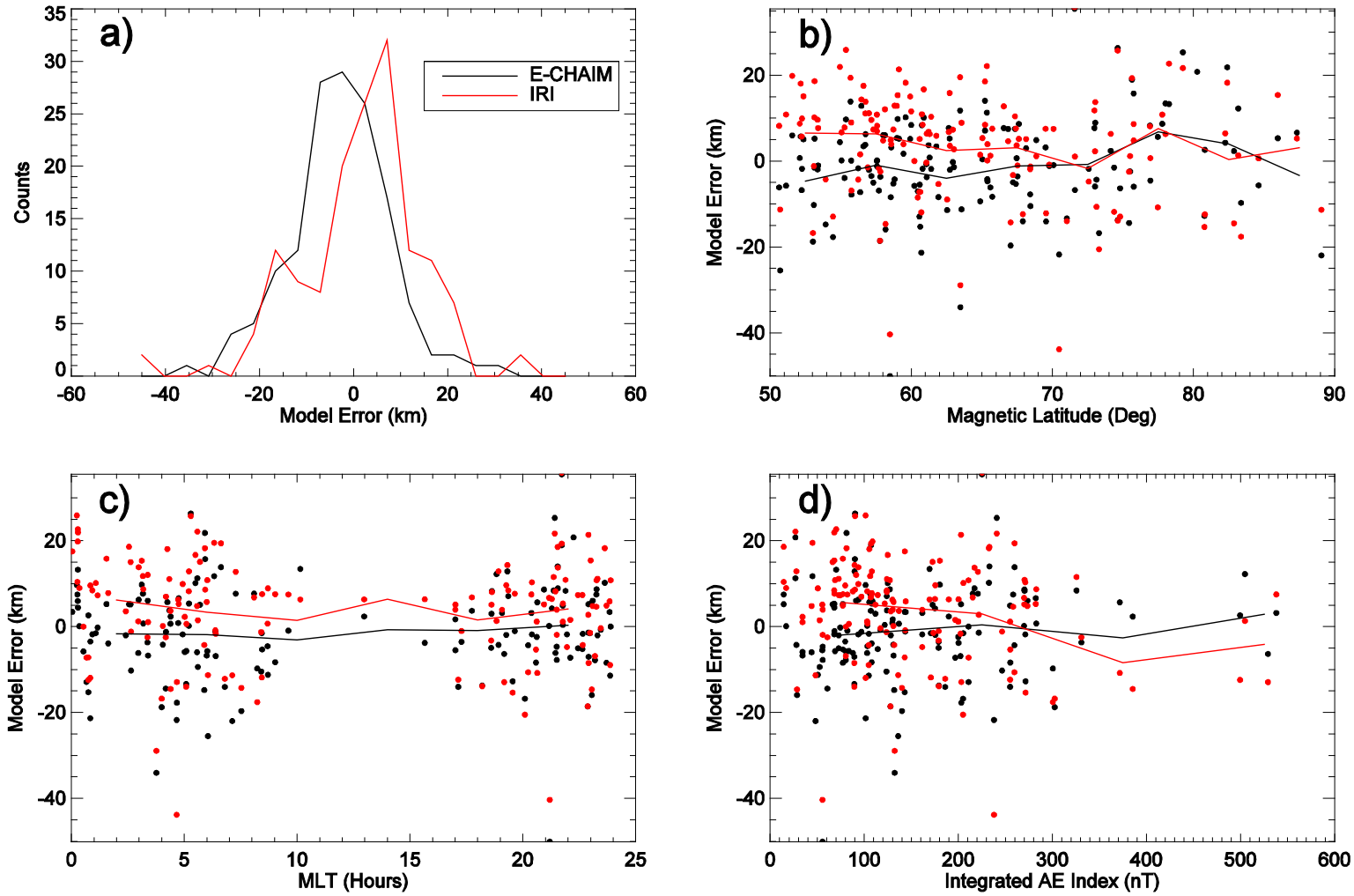
Fitting Performance vs. IRI



Fitting Performance vs. IRI

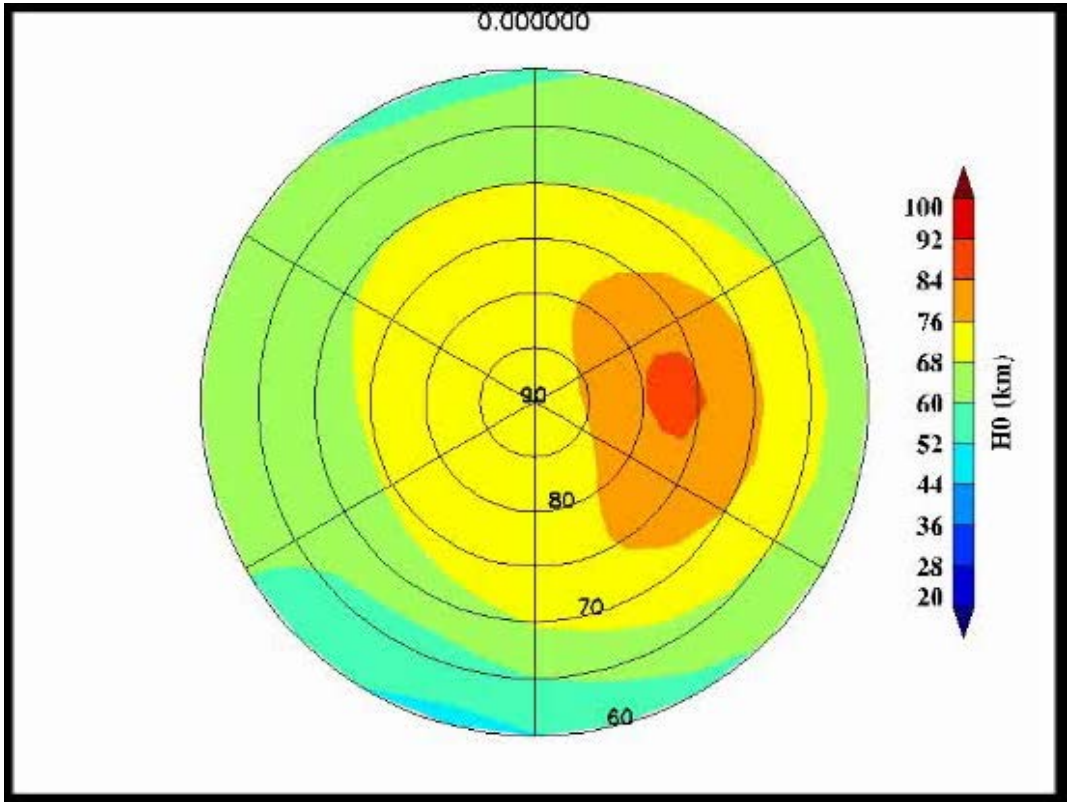


Validation vs. ePOP GAP Radio Occultation Profiles



What does storm variability look like? 192 hours beginning May 30th, 2013

- Plotted in MLT and MLat.
- See UT-dependant diurnal pattern, likely coming from the sol. zen. terms.
- Kp 7 geomagnetic storm begins at hour 44, peaking at hour 56.



Conclusions

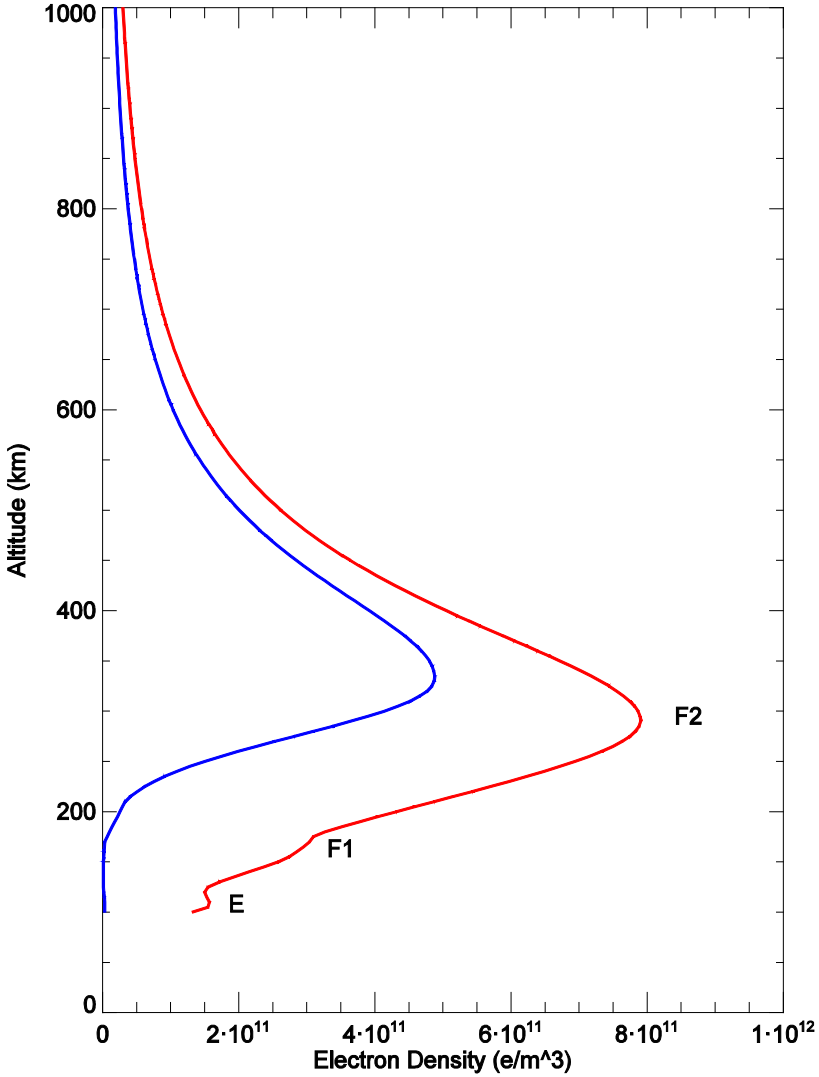
- E-CHAIM outperforms the IRI in the representation of topside thickness.
- Even directly refitting the NeQuick parameterization does not fix the significant issues in the IRI's representation of diurnal, seasonal, and solar cycle variability.
- The E-CHAIM provides a storm-time representation of topside thickness that represents a significant improvement over the IRI.

Thank you

- We would like to thank all of the data providers for their incredible contributions of high quality data to this project:
- ISR: Phil Erickson, Anja Stromme, Anthony Vaneyk, Roger Varney, Ingemar Häggström, Mykhaylo Lyashenko, and the SRI International, Haystack, and EISCAT teams (special thanks to Bill Rideout for working through the Madrigal IDL API with me).
- Topside Sounder: Dieter Bilitza and the CRC.
- Radio Occultation: The University Corporation for Atmospheric Research (UCAR), Chris Watson (e-POP), and Richard Langley (e-POP).

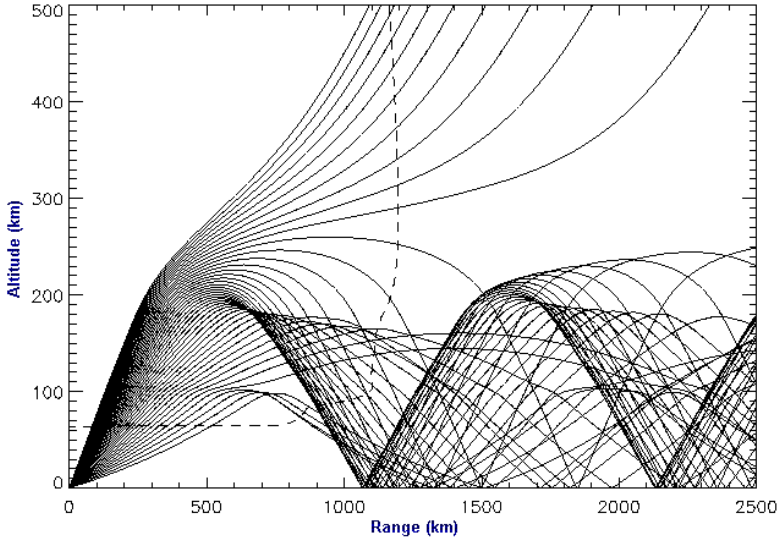
The Ionosphere

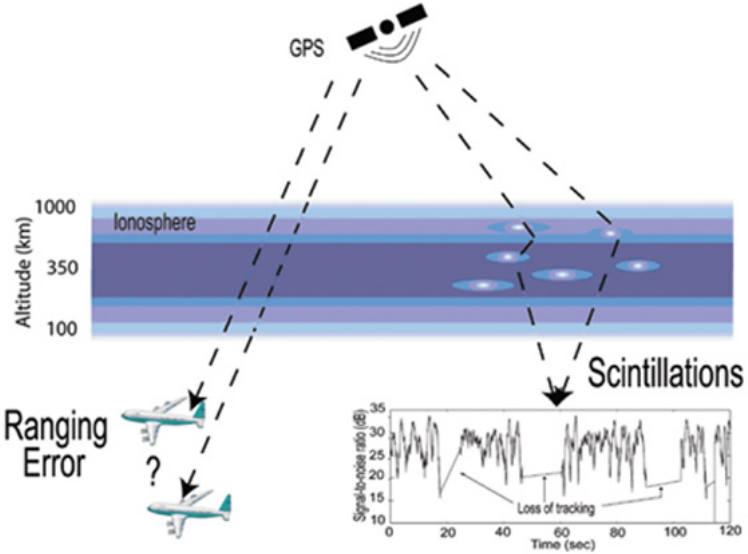
- Ionized layer of the upper atmosphere between ~80km and 1000km.
- Formed by photo-ionization of atmospheric constituents.
- Highly coupled to the magnetic field.



Why do we care about the ionosphere?

- Medium and reflecting surface for HF Radio communications.
- Range errors and loss of signal from UHF positioning systems.
- Distortion in radio telescope imaging.





Why E-CHAIM?

- There are several different models of the ionosphere that are relatively accurate at mid-latitudes.
- The most successful models are empirical or based on data assimilation; however, physics-based models do exist (popular as background in assimilation).
- Little data has been available in the high latitude region in the past, making the performance of these models suspect in these regions.

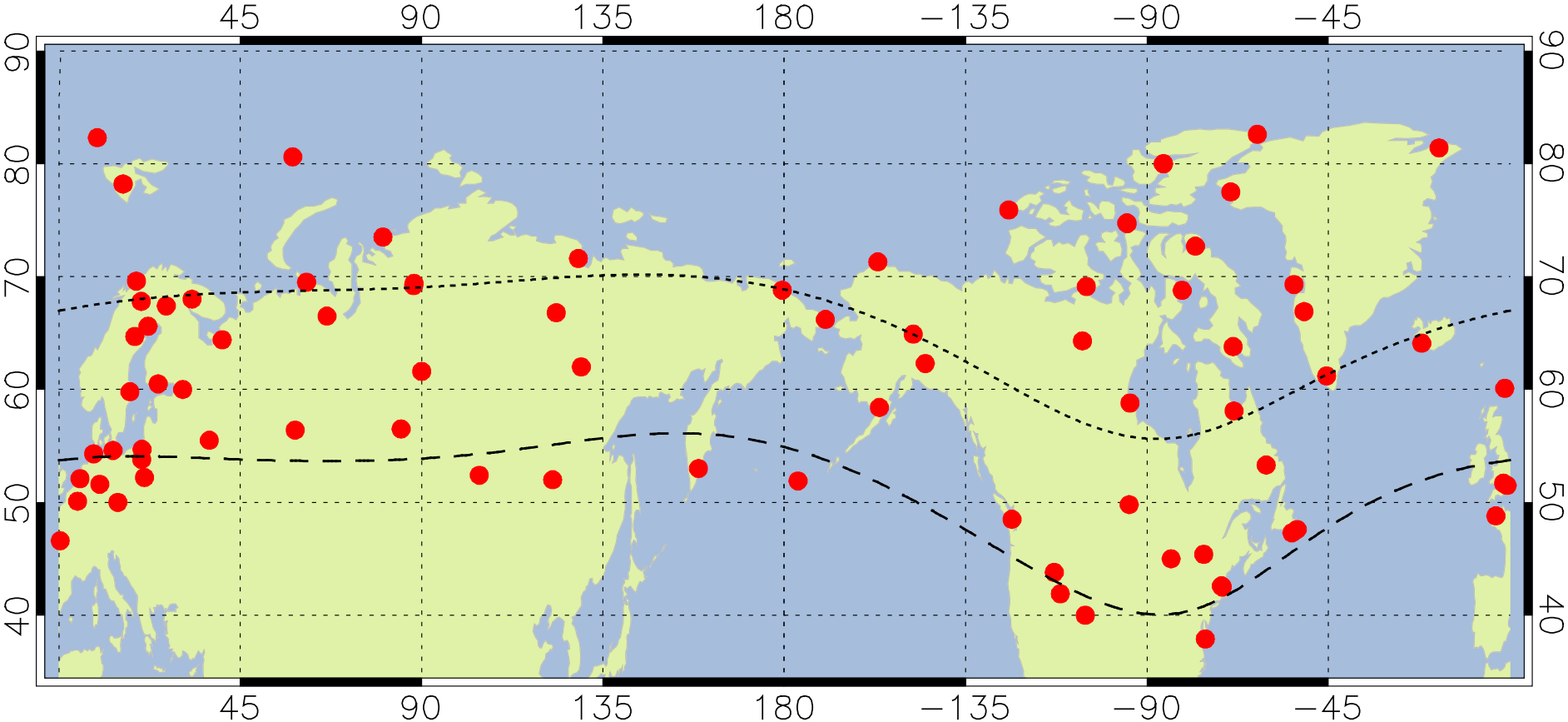
Example: The International Reference Ionosphere (IRI)

- The de facto model for ionospheric specification recognized by the International Standards Organization.
- Errors in peak density at times in excess of 70% during equinoxes.
- Issues representing ionospheric variations resulting from short term (less than 1 year) variations in solar activity.
- Occasional diurnal variability patterns that are the complete opposite to those of observations.

Empirical-CHAIM

- A empirical climatological model designed to replace the use of the IRI at high latitudes.
- We make use of a decade worth of IRI validation studies to avoid identified issues in empirical ionospheric modeling, adapting the IRI approach to reflect these issues.
- The horizontal structure of the ionosphere is represented by a Spherical Cap Harmonic Expansion.
- Built from GPS, Ionosonde, Incoherent Scatter Radar, and Radio Occultation data.

Data



Over 28 million ionosonde observations from 82 instruments operated between 1931 and 2016 and gathered from 15 different data portals.

Quality Control and Analysis

- Every data source has a different data format and applies different processing methods.
- Only a select few data sources provide error estimates or quality control indices.
- Ionosonde data is traditionally very difficult to automatically process, particularly at high latitudes.
- Suspect data points are identified automatically and were manually assessed.

Last Year's Current Work/Issues

- "*Currently in the empirical model fitting stage.*
- *Facing challenges, namely in identifying an optimal coordinate system, optimizing the model parameterization, and in finding the necessary computing power/memory in order to undertake the fits. (Trial and error + ACENet).*
- *Still need to get a hold of electron density profiles, not just summary characteristics."*

The Model: NmF2

$$\log(NmF2) = G + \sum_{l=0}^{L} \sum_{m=0}^{\min(l,M)} \left[A_{lm} \cos\left(\frac{\pi m}{180}\lambda\right) + B_{lm} \sin\left(\frac{\pi m}{180}\lambda\right)\right] P_{lm}(\eta)$$

$$\eta = \cos\left((90 - \varphi)\frac{\pi}{45}\right) \qquad L = 5, \mathrm{M} = 4, \mathrm{c} = 4$$

$$A_{lm}, B_{lm} = (\gamma_{lm} F_1 + \delta_{lm} F_2) \cdot sin^2\left(\frac{\pi \cdot DoY}{365.25}\right) + (C_{lm} F_1 + D_{lm} F_2)$$

$$C_{lm}, D_{lm} = \sum_{c=1}^{4} \alpha_{lm}^{c} \cos\left(\frac{2\pi c \cdot DoY}{365.25}\right) + \beta_{lm}^{c} \sin\left(\frac{2\pi c \cdot DoY}{365.25}\right)$$

G=

$$F10.7 \cdot (a_1 \cos(\chi) + a_2 \sin(\chi)) + \sqrt{F10.7} \cdot (a_3 \cos(\chi) + a_4 \sin(\chi)) + IG \cdot (a_5 \cos(\chi) + a_6 \sin(\chi)) + a_7 F10.7^2 \cos(\chi) + a_8 IG^2$$

$$F_1 = F10.7_{81} \qquad F_2 = (F10.7_{81})^{(1/1.9)}$$

Modeling Spatial Structure

- The horizontal structure of NmF2 and hmF2 is modeled using a spherical cap harmonic expansion.
- The degree and order of the expansion was chosen while balancing increased horizontal resolution with increased measurement noise.

$$\log(NmF2) = G + \sum_{l=0}^{L} \sum_{m=0}^{\min(l,M)} A_{lm} \cos\left(\frac{\pi m}{180}\lambda\right) + B_{lm} \sin\left(\frac{\pi m}{180}\lambda\right) P_{lm}(\eta)$$

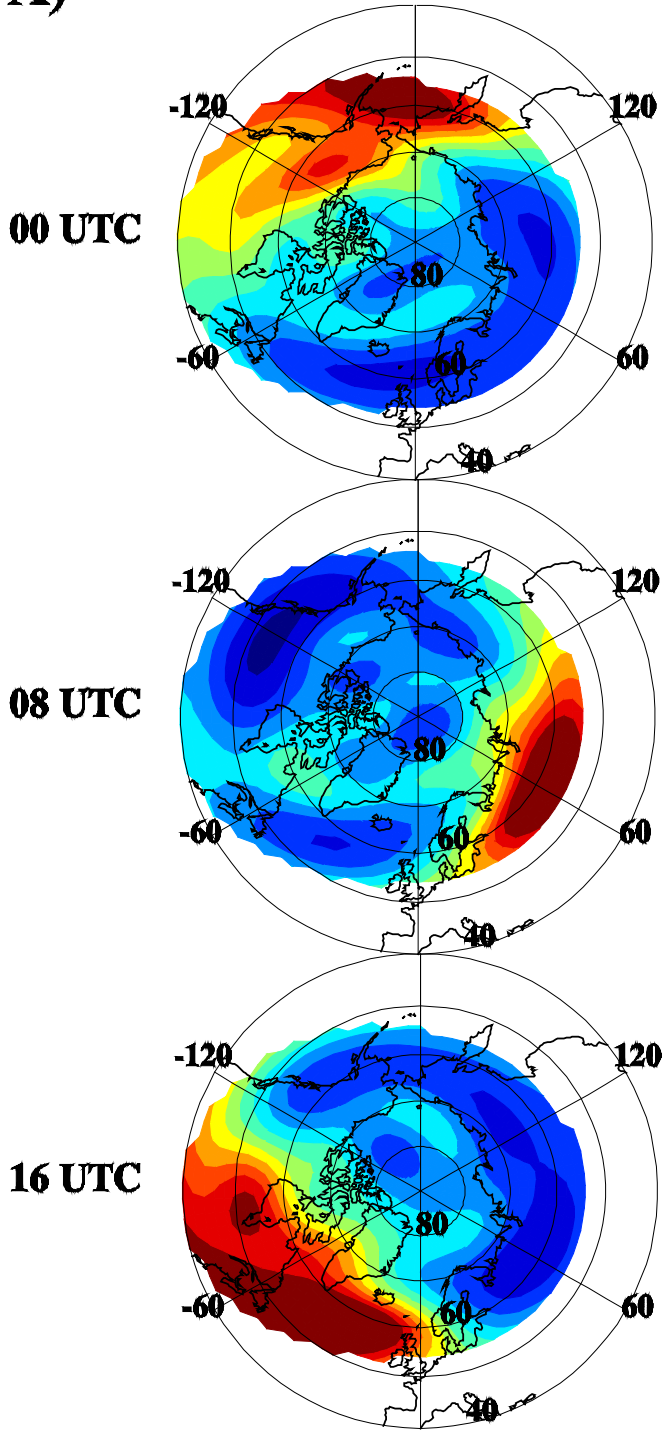
$$\eta = \cos\left((90 - \varphi)\frac{\pi}{45}\right) \qquad L = 5, \mathrm{M} = 4, \mathrm{c} = 5$$

Coordinate System and Diurnal Variability

- Traditionally, empirical models have used a local time coordinate for longitude and a modified dip angle for latitude.
- At high latitudes, ionospheric dynamics are strongly driven by both solar factors and coupling to the magnetic field.
- Separation of the geographic and geomagnetic poles thereby does not allow us to make a local time simplifying assumption.

Coordinate System: E-CHAIM

- Option #1: Fit the model with a normal longitude coordinate and add in more coefficients to take care of diurnal variability.
  - No more issues about local time assumptions.
  - Much bigger model (28mil x seasonal_spatial_terms x diurnal_terms = inverting an ~84 billion x ~84 billion element array)
- Option #2: Fit a map to each UTC hour separately:
  - No more issues about local time assumptions.
  - Takes care of diurnal variability.
  - Means we no longer have to fit all 28+ million data points at once to a large model.
  - Need to be careful, as the model's are completely separately fit.


00 UTC
08 UTC
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-120
120
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60
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60
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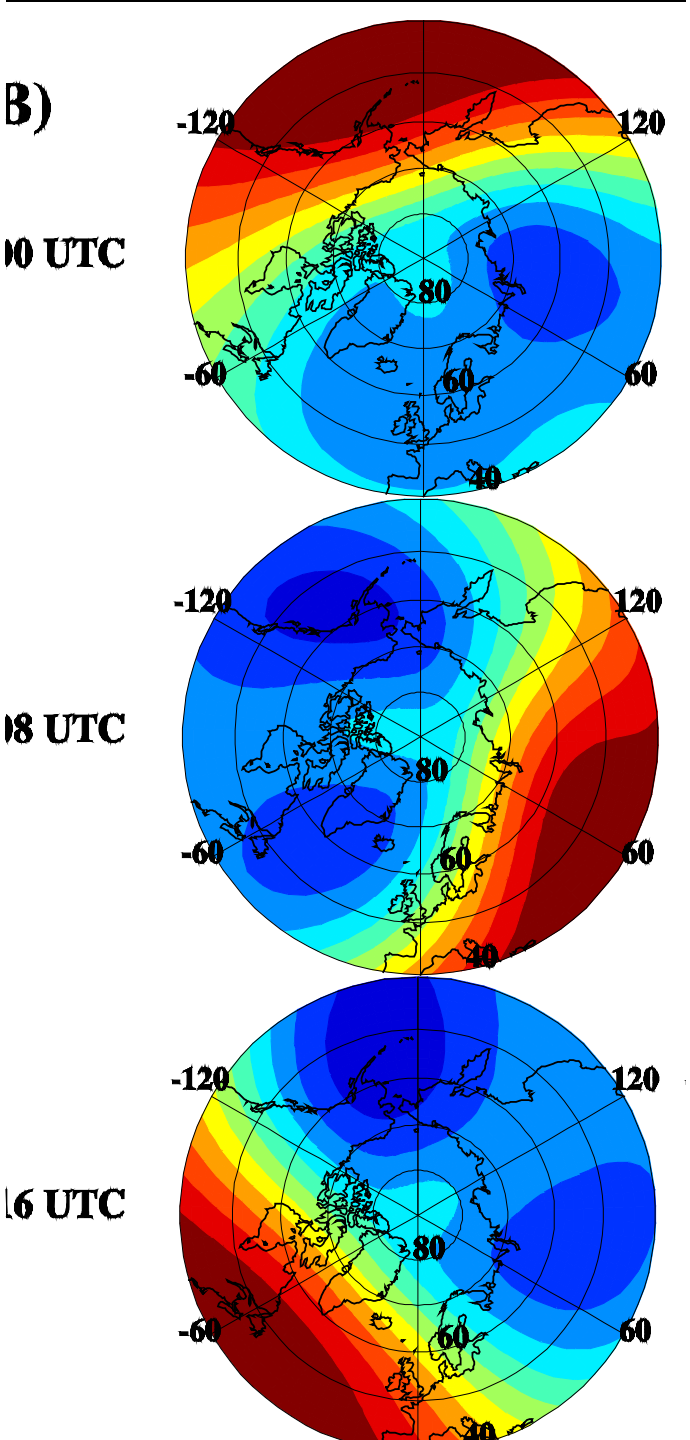

B)
-120
120
-60
60
80
60
40

Solar Activity Variability

- NmF2 generally varies linearly with solar F10.7 flux but sometimes saturates at high solar activities or becomes slightly parabolic during the winter.
- Saturation is most common at mid- and low-latitudes but occurs at high latitudes during the summer.

Solar Activity Variability in E-CHAIM

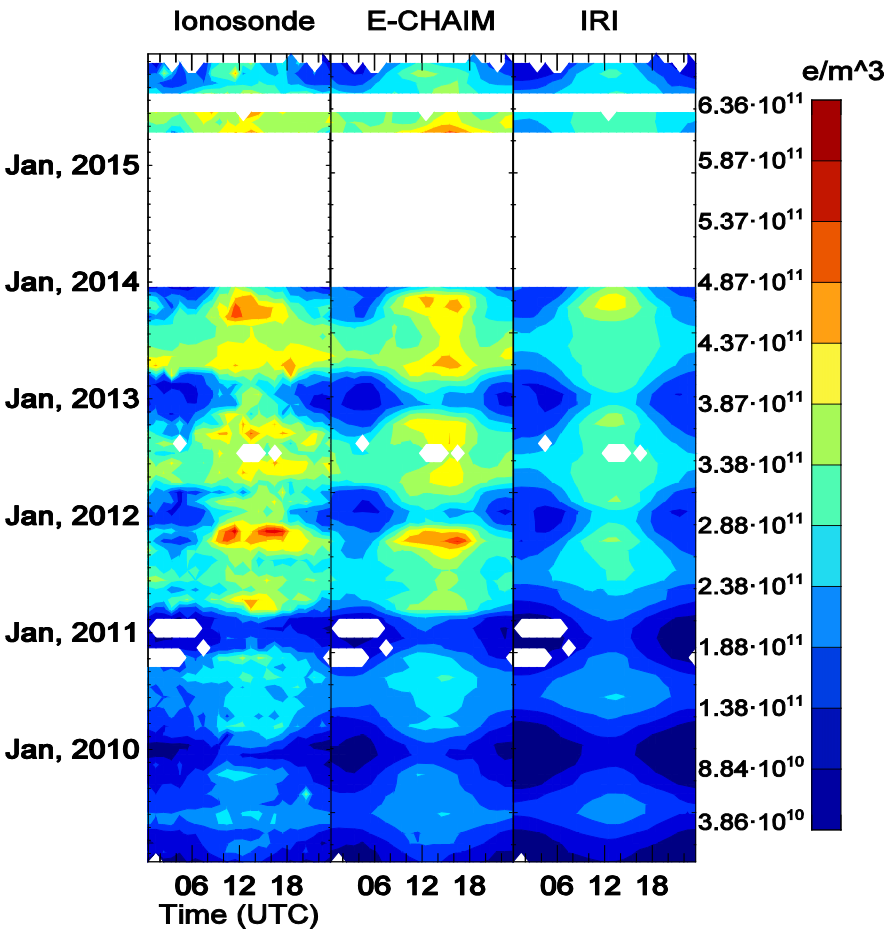
- Use 81-day-(3 solar rotation) smoothed F10.7 flux as the driving solar proxy.
- Added additional terms with the IG (ionosonde-derived index) and 81-day-smoothed F10.7 flux.

$$F_1 = F10.7_{81} \qquad F_2 = (F10.7_{81})^{(1/1.9)}$$

$$\mathrm{G} = F10.7 \cdot (a_1 \cos(\chi) + a_2 \sin(\chi)) + \sqrt{F10.7} \cdot (a_3 \cos(\chi) + a_4 \sin(\chi)) + IG \cdot (a_5 \cos(\chi) + a_6 \sin(\chi)) + a_7 F10.7^2 \cos(\chi) + a_8 IG^2$$

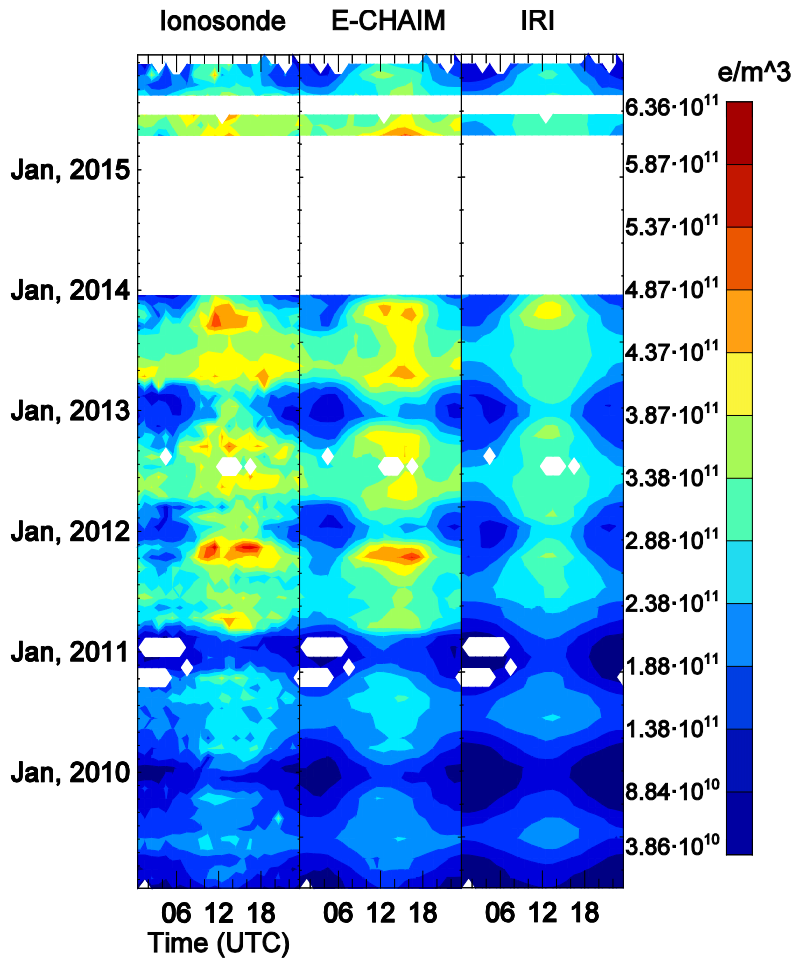
Seasonal Variability

- Simple Fourier Expansion in Day of Year (DoY).
- Up to quintenial variations are modeled.

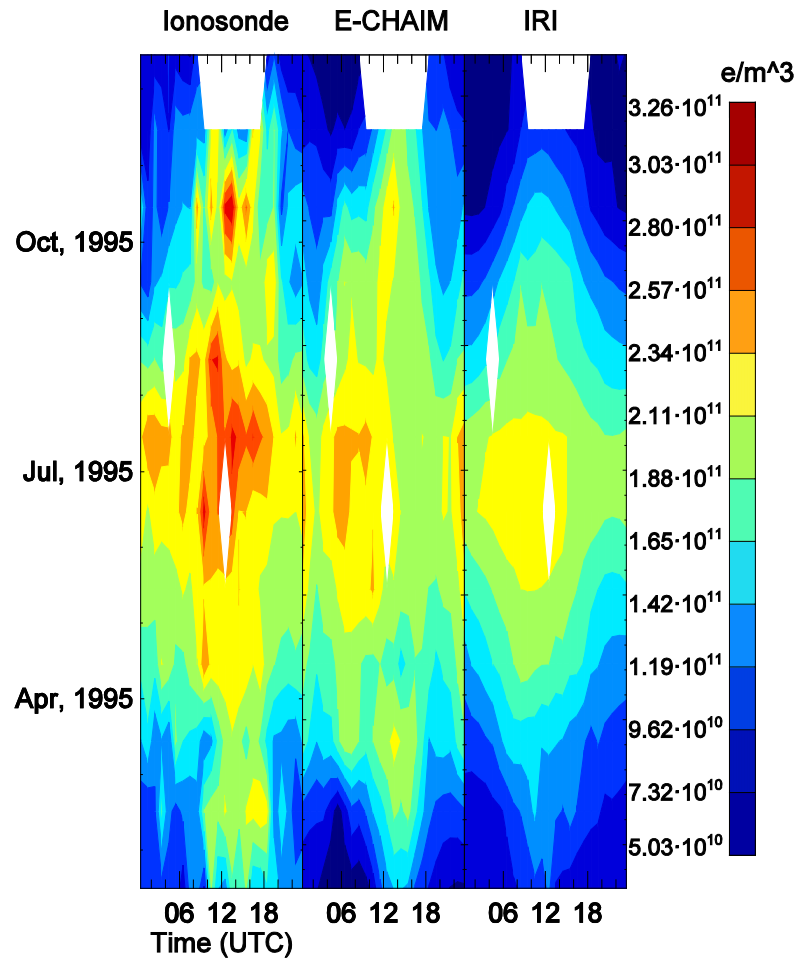


$$C_{lm}, D_{lm} = \sum_{c=1}^{5} \alpha_{lm}^{c} \cos\left(\frac{2\pi c \cdot DoY}{365.25}\right) + \beta_{lm}^{c} \sin\left(\frac{2\pi c \cdot DoY}{365.25}\right)$$

Examples

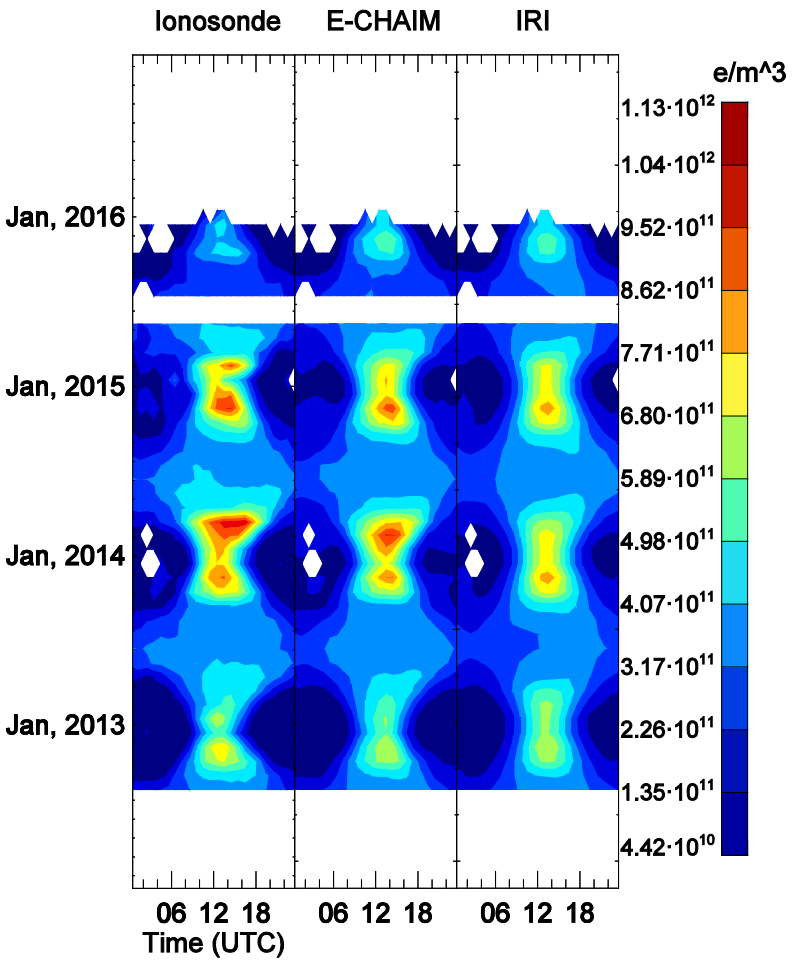


Resolute

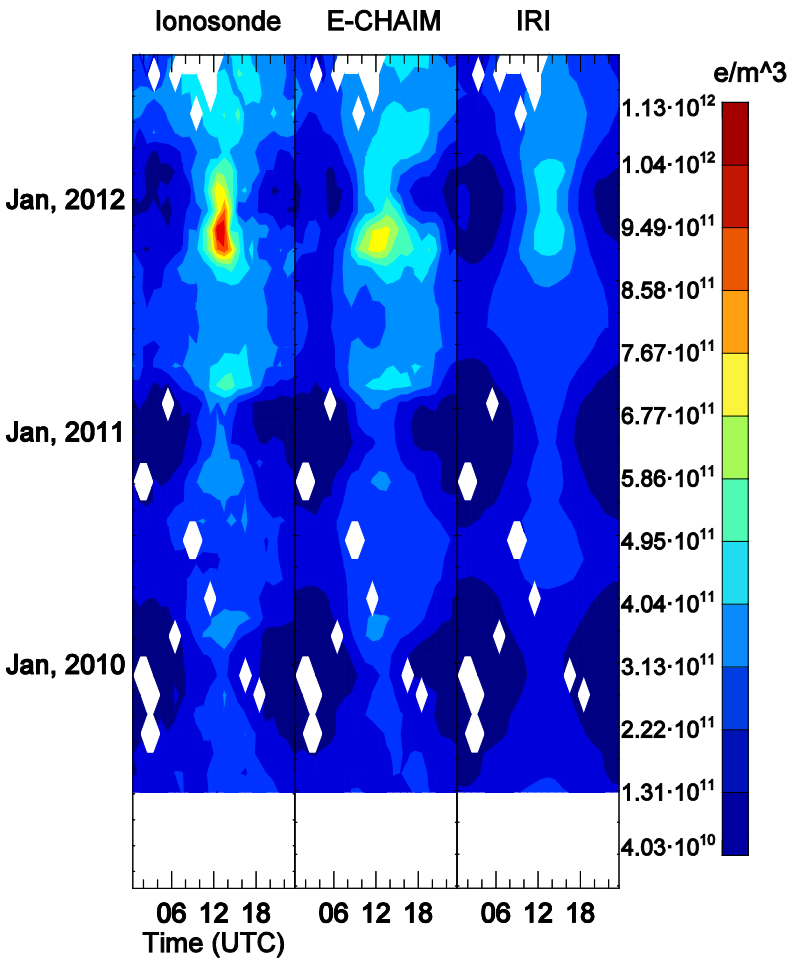


Alert

Examples (cont.)

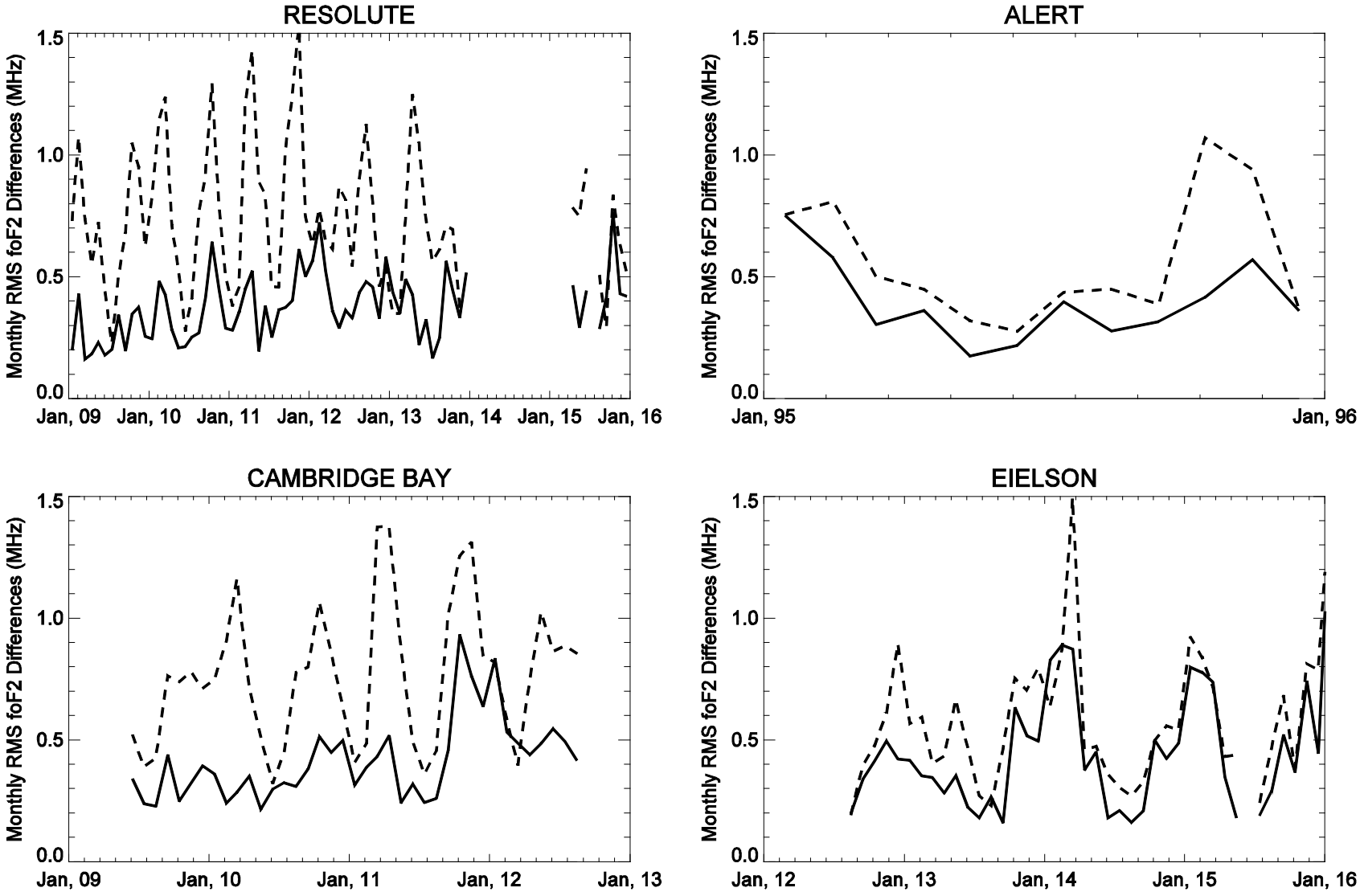


Eielson



Cambridge Bay

RMS Performance



Ionospheric Storms

- The IRI features an adjustment to account for storm-time ionospheric variability.
- While climatological models such as the IRI and E-CHAIM cannot be expected to fully capture these variabilities (particularly those on short timescales), storm adjustments should constitute some improvement over the climatology.

Storm Model

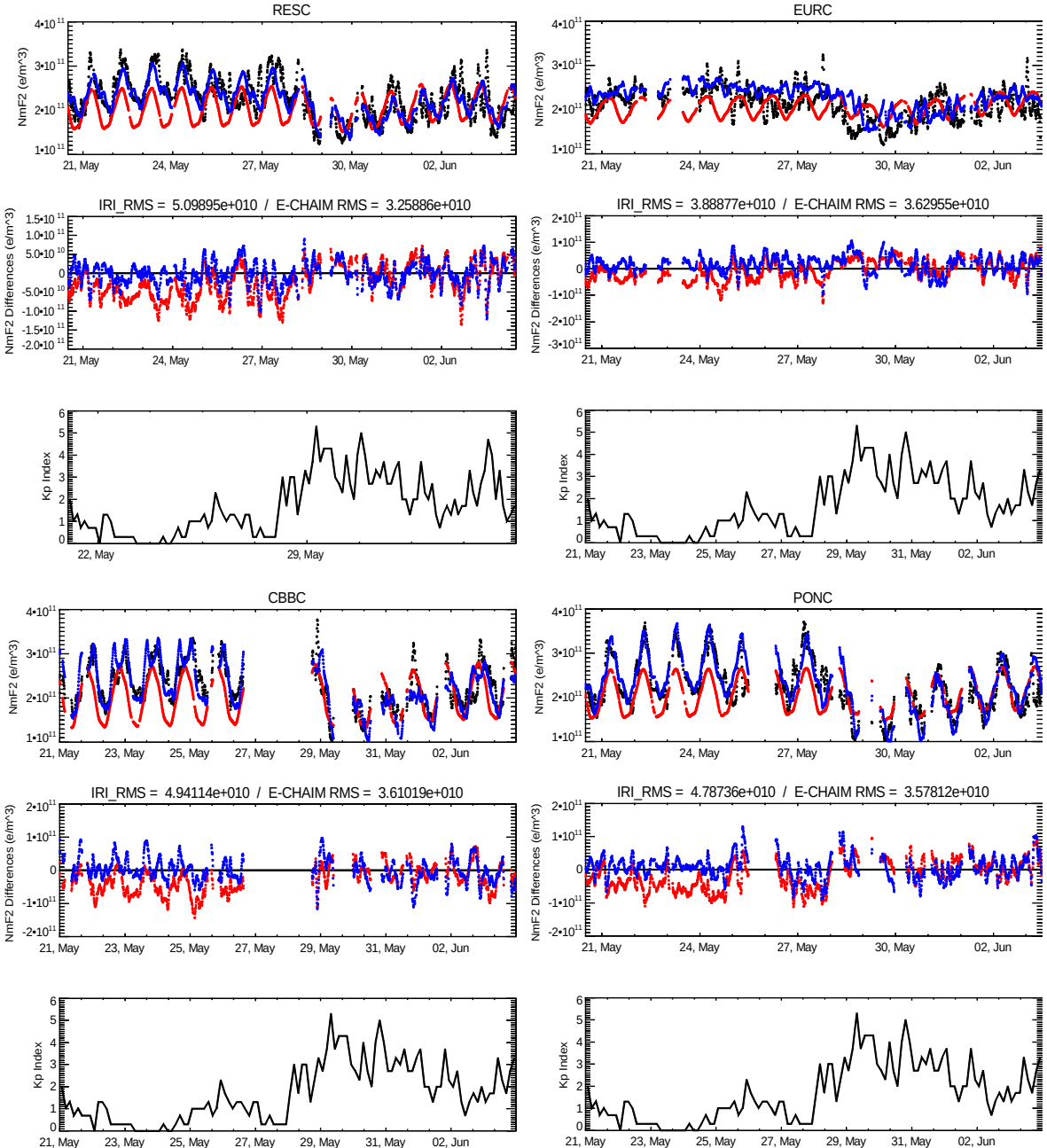
- We use a similar concept to the IRI:
  - Geomagnetic activity indices integrated over 12-36hour periods to drive storm-time ionospheric perturbations.

$$\log\left(\frac{NmF2}{\overline{NmF2}}\right) = \sum_{l=0}^{L} \sum_{m=0}^{\min(l,M)} \left[A_{lm}\cos\left(\frac{\pi m}{180}\lambda\right) + B_{lm}\sin\left(\frac{\pi m}{180}\lambda\right)\right] P_{lm}(\eta)$$

$$A_{lm}, B_{lm} = \sum_{d=1}^{3} \left(\alpha_{lm}\sin\theta + \beta_{lm}\cos\theta + (\gamma_{lm}\sin\theta + \delta_{lm}\cos\theta)\sqrt{F10.7}\right) G_d$$

$$\mathrm{G} = e^{Dst/300}, e^{-ap/30}, e^{AE/700}$$

Evaluation: May 21 – June 5, 2010



Summary

- E-CHAIM constitutes a significant and universal improvement over the IRI in the representation of NmF2.
- While still underestimating solar activity and seasonal variability by 5-15%, E-CHAIM easily outperforms the IRI's 30-50% variability underestimation.
- The use of the storm perturbation adjustment results in a 15-40% improvement over the climatological E-CHAIM model representation during storm periods.

Current Status

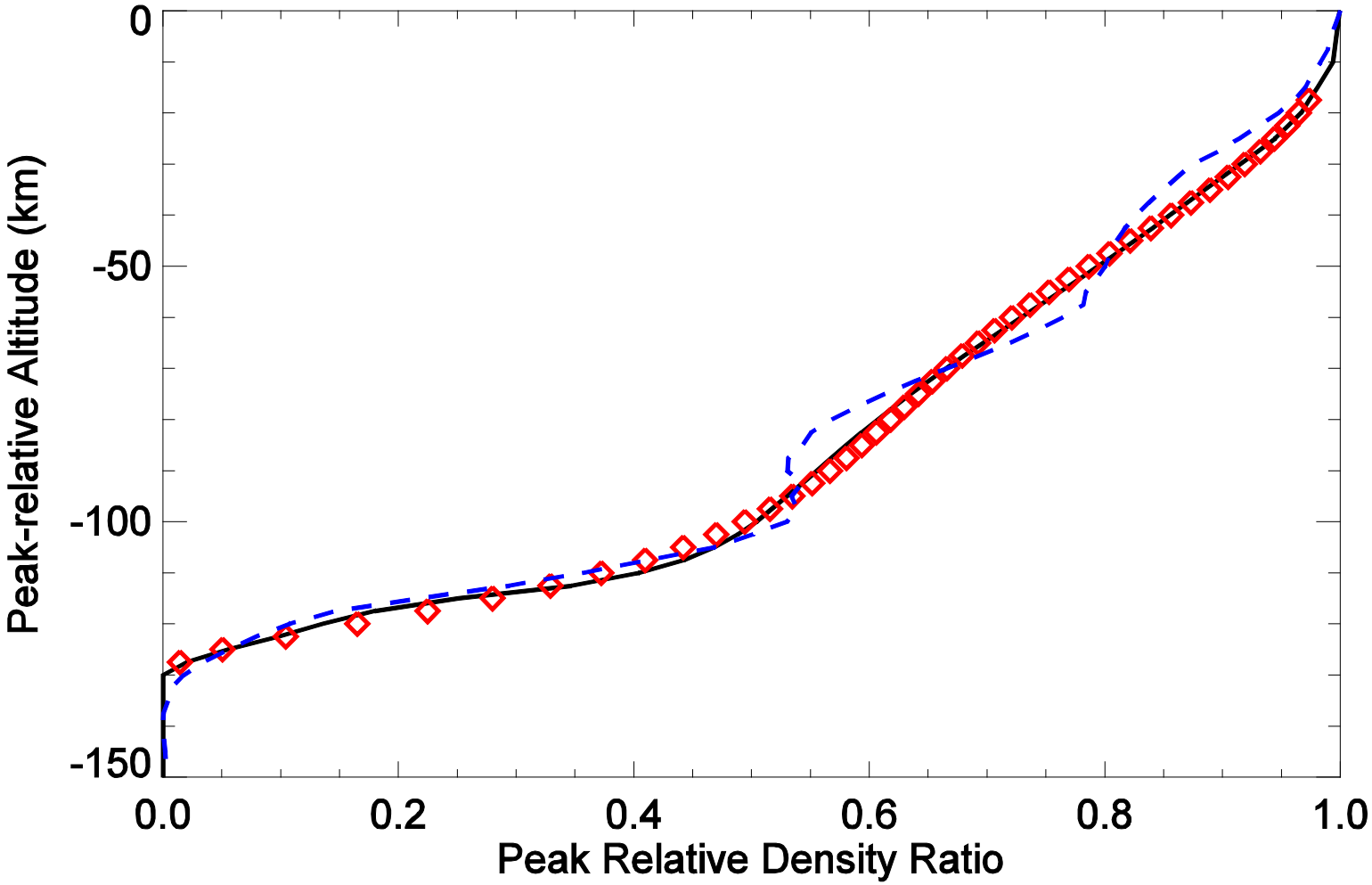
hmF2: Complete

Eleison Cambridge Bay Resolute

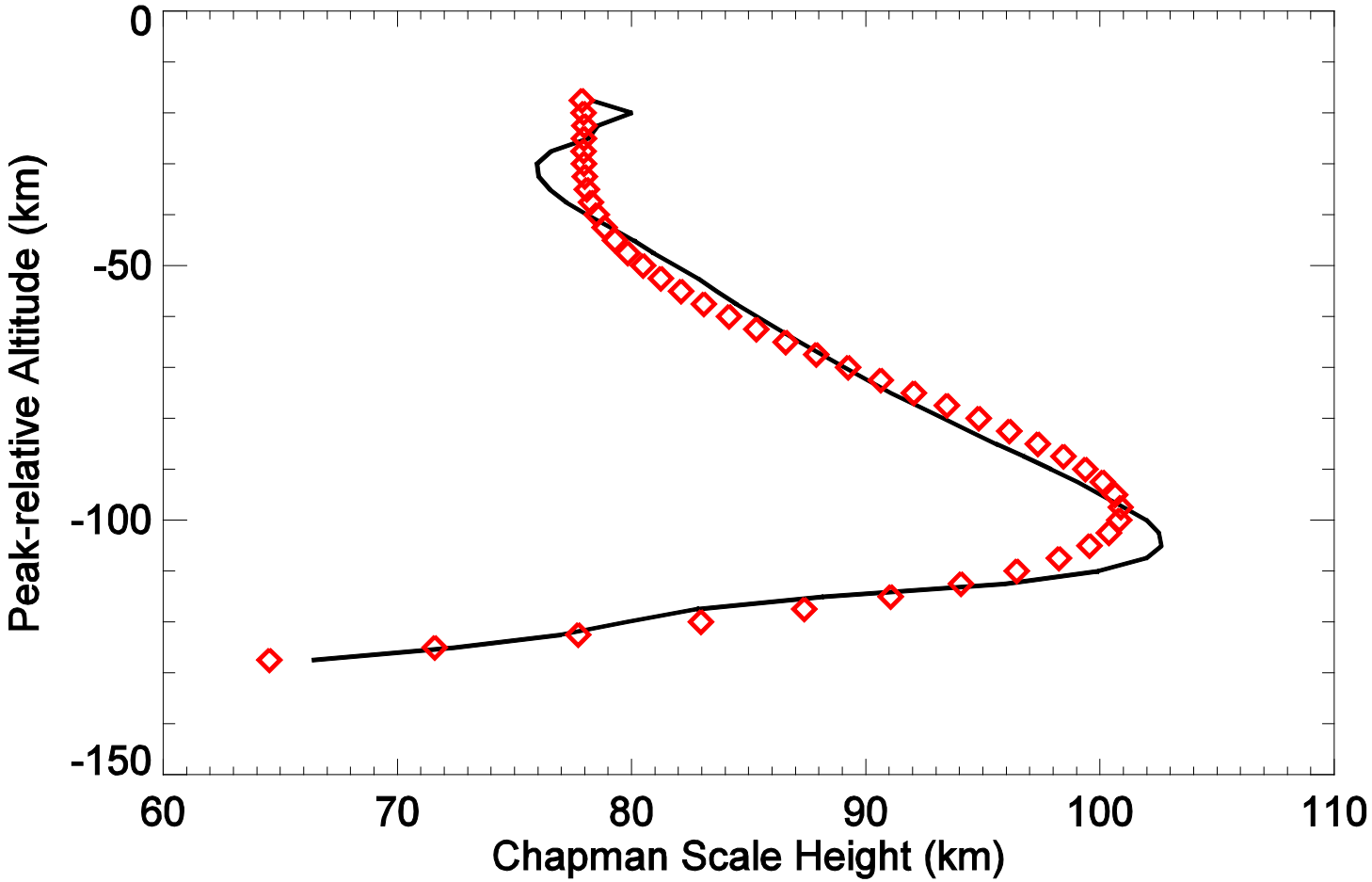
Bottomside Parameterization

- Originally wanted to use Empirical Orthogonal Functions (EOFs) to represent the bottomside vertical structure of the E-CHAIM ionosphere, but E and F1 profile inflections are not sufficiently statistically important with respect to F-layer thickness variability.
- Also, EOFs are not explicitly differentiable, leading to the potential for discontinuities in the profile shape.
- Instead, we'll fit to a Chapman function with variable scale height.
- E and F1 inflections will be fitted separately after the dominant F-region variations are removed.

Example


0
-50
-100
-150
Peak-relative Altitude (km)
0.0
0.2
0.4
0.6
0.8
1.0
Peak Relative Density Ratio

Scale Height



Topside

- Incoherent Scatter Radar and Radio Occultation electron density profiles have been fitted to a semi-epstein layer function.
- Only the layer thickness will need to be modeled explicitly.
- This thickness will be fitted to a similar expansion as that which was used for NmF2.

Conclusion

- The first two phases of the E-CHAIM model, namely the NmF2 and hmF2 parameterizations are now complete.
- NmF2 and hmF2 are demonstrating significant performance improvements over the use of the IRI.
- The bottomside and topside parameterization fitting is now underway.

Supplementary Slides

$$n^2 = 1 - \frac{X\left(1-X\right)}{1 - X - \frac{1}{2}Y^2\sin^2\theta \pm \left(\left(\frac{1}{2}Y^2\sin^2\theta\right)^2 + \left(1-X\right)^2 Y^2\cos^2\theta\right)^{1/2}}$$

$$X = \frac{\omega_0^2}{\omega^2}$$

$$Y = \frac{\omega_H}{\omega}$$

$$Z = \frac{\nu}{\omega}$$