The Empirical Canadian High Arctic Ionospheric Model (E-CHAIM): NmF2

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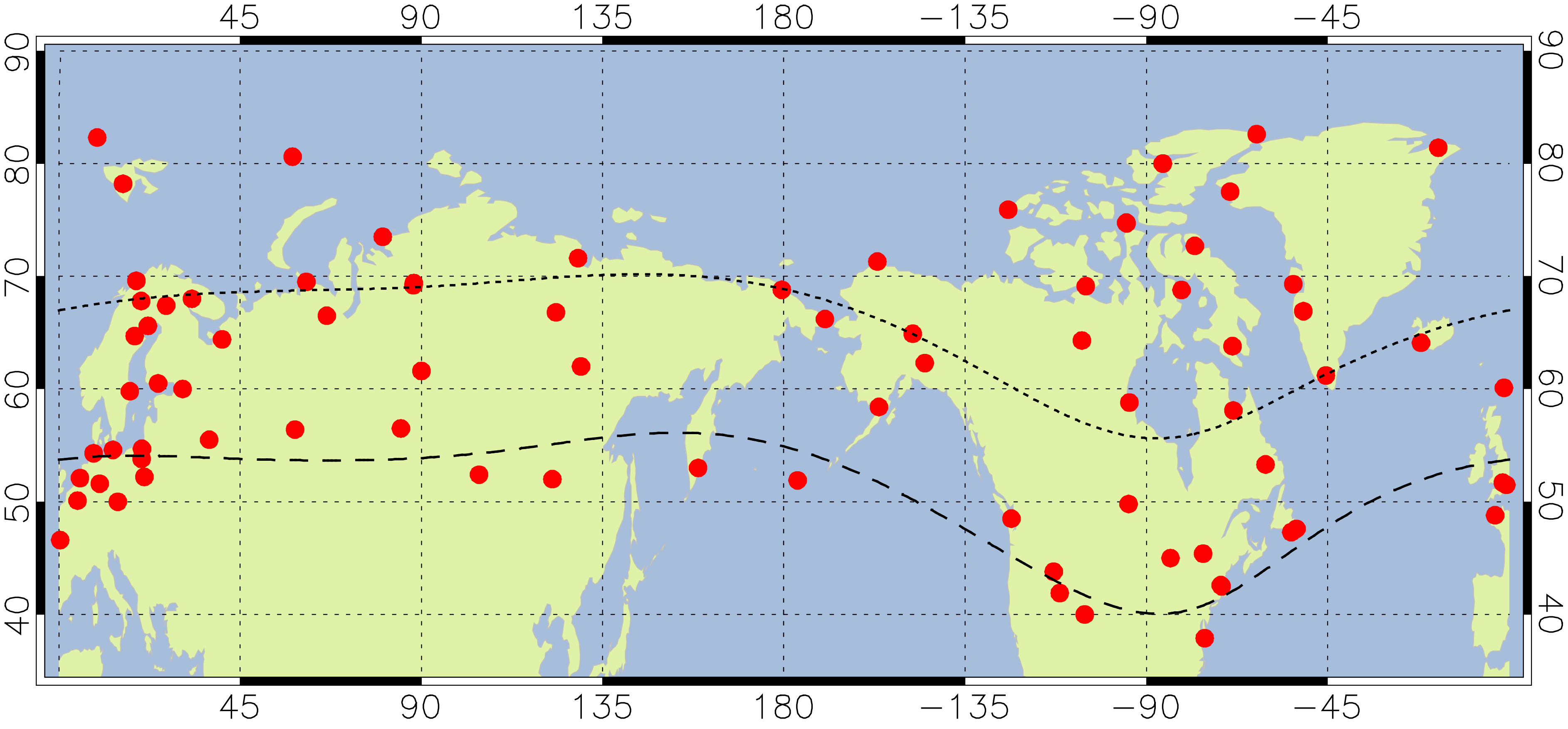
Outline

- Introduction of the dataset.
- Climatological Model Parameterization
- Validation of the Climatological Model and Comparisons to the IRI.
- Storm Model Parameterization
- Examples of Storm Model Performance and Comparisons to the IRI.

Empirical-CHAIM

- An 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 topside sounder, Ionosonde, Incoherent Scatter Radar, and Radio Occultation data.

Data: Ionosonde



Over 28 million ionosonde observations from 82 instruments operated between 1931 and 2016 and gathered from 8 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 (~10% of the dataset).

Data: 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.

Challenges: Coordinate System, Diurnal Variability, and Dataset Size

- 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 coordinate simplification.
- With a dataset this large, processing the whole dataset at once is very computationally challenging.
- Solution: Fit 24 separate models (one for each UTC hour)

The Model: NmF2

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

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

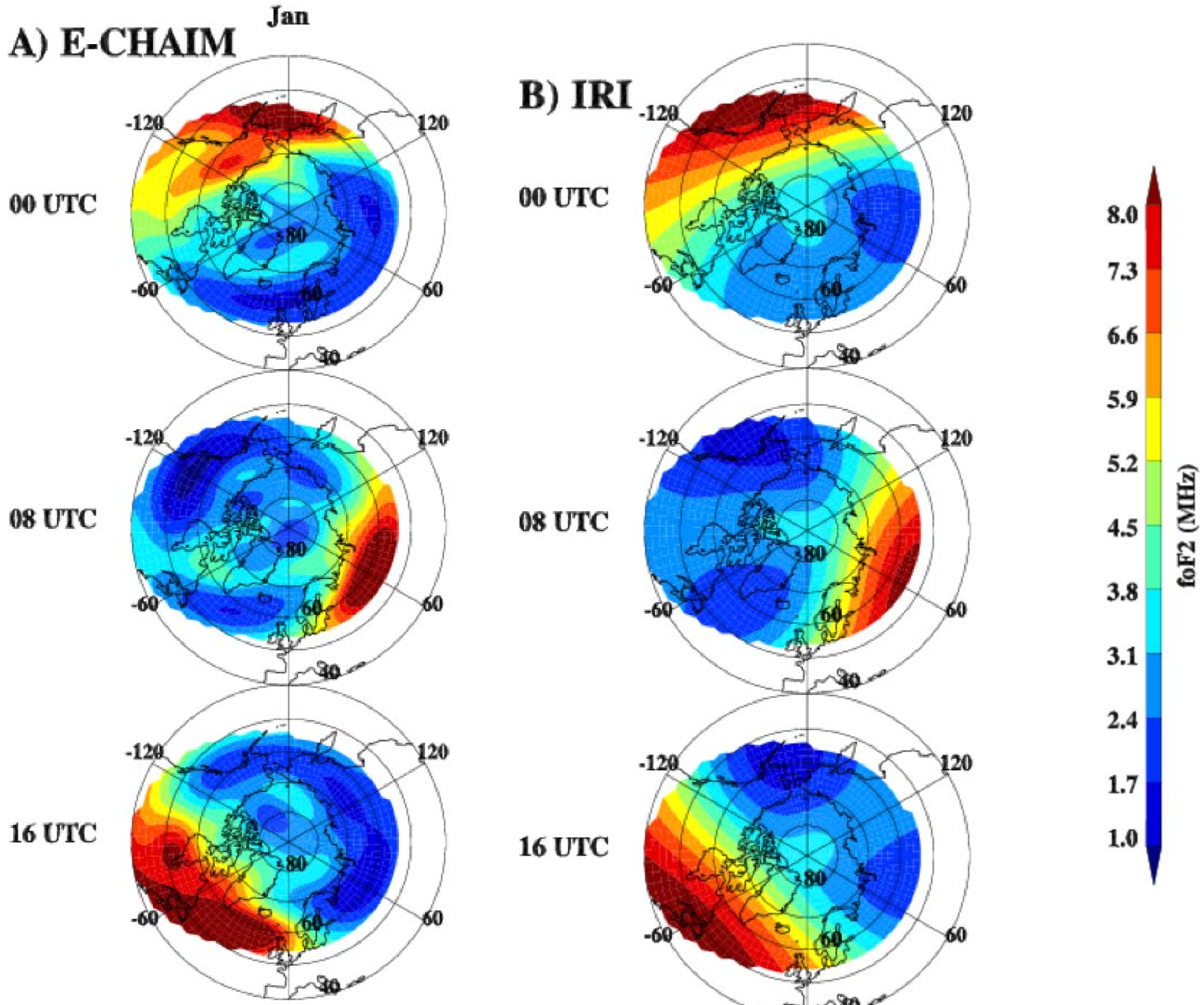
$$A_{lm}, B_{lm} = (\gamma_{lm} F_1 + \delta_{lm} F_2) \cdot sin^2\left(\frac{\pi \cdot DoY}{365.25}\right) + (C_{lm} F_1 + D_{lm} F_2)$$

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

G=

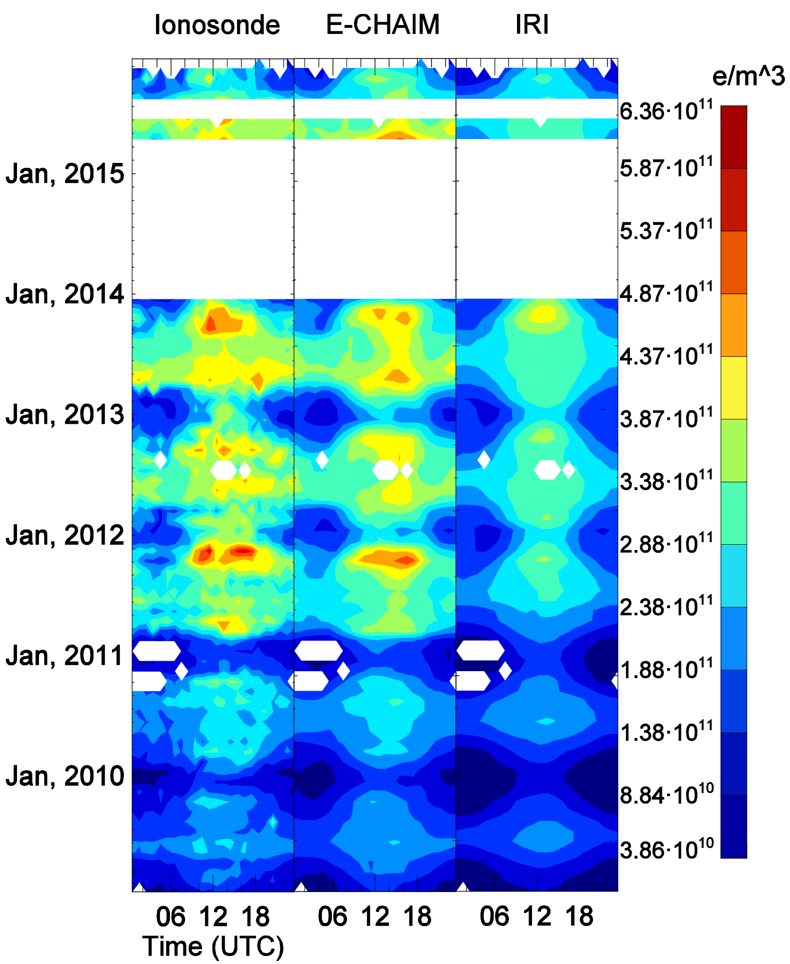
$$F10.7 \cdot (a_1 \cos(\chi) + a_2 \sin(\chi)) + \sqrt{F10.7} \cdot (a_3 \cos(\chi) + a_4 \sin(\chi)) + IG \cdot (a_5 \cos(\chi) + a_6 \sin(\chi)) + a_7 F10.7^2 \cos(\chi) + a_8 IG^2$$

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

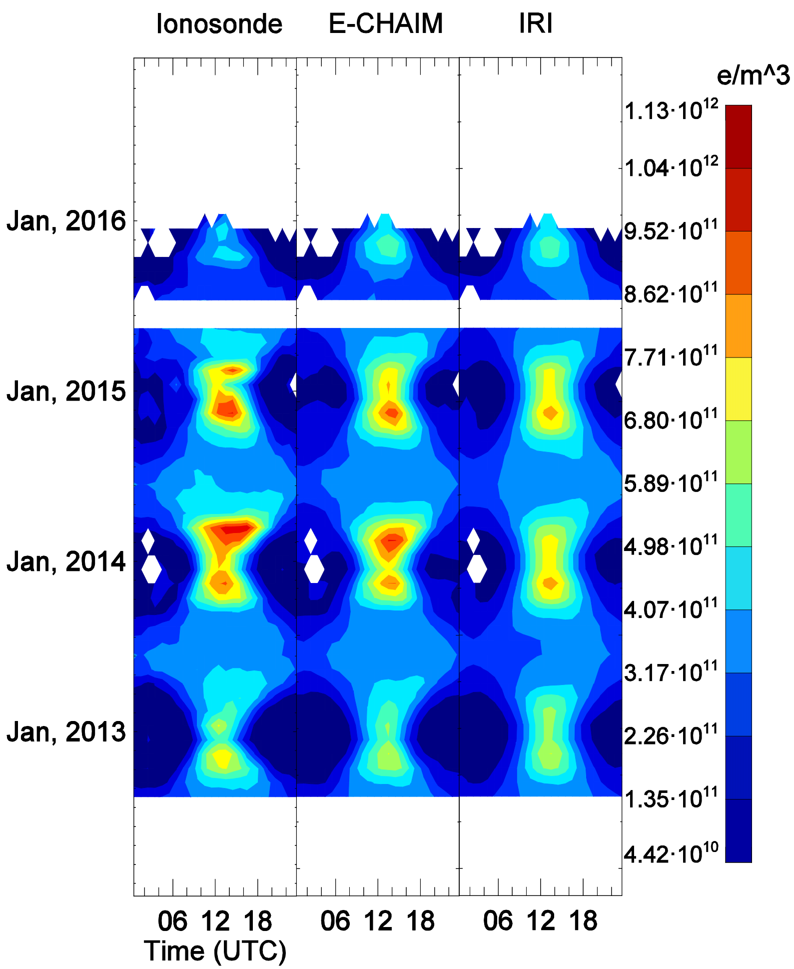


Jan
A) E-CHAIM
B) IRI
00 UTC
08 UTC
16 UTC
-120
120
-60
60
80
60
30
8.0
7.3
6.6
5.9
5.2
4.5
3.8
3.1
2.4
1.7
1.0
foF2 (MHz)

Comparison to IRI and Ionosonde

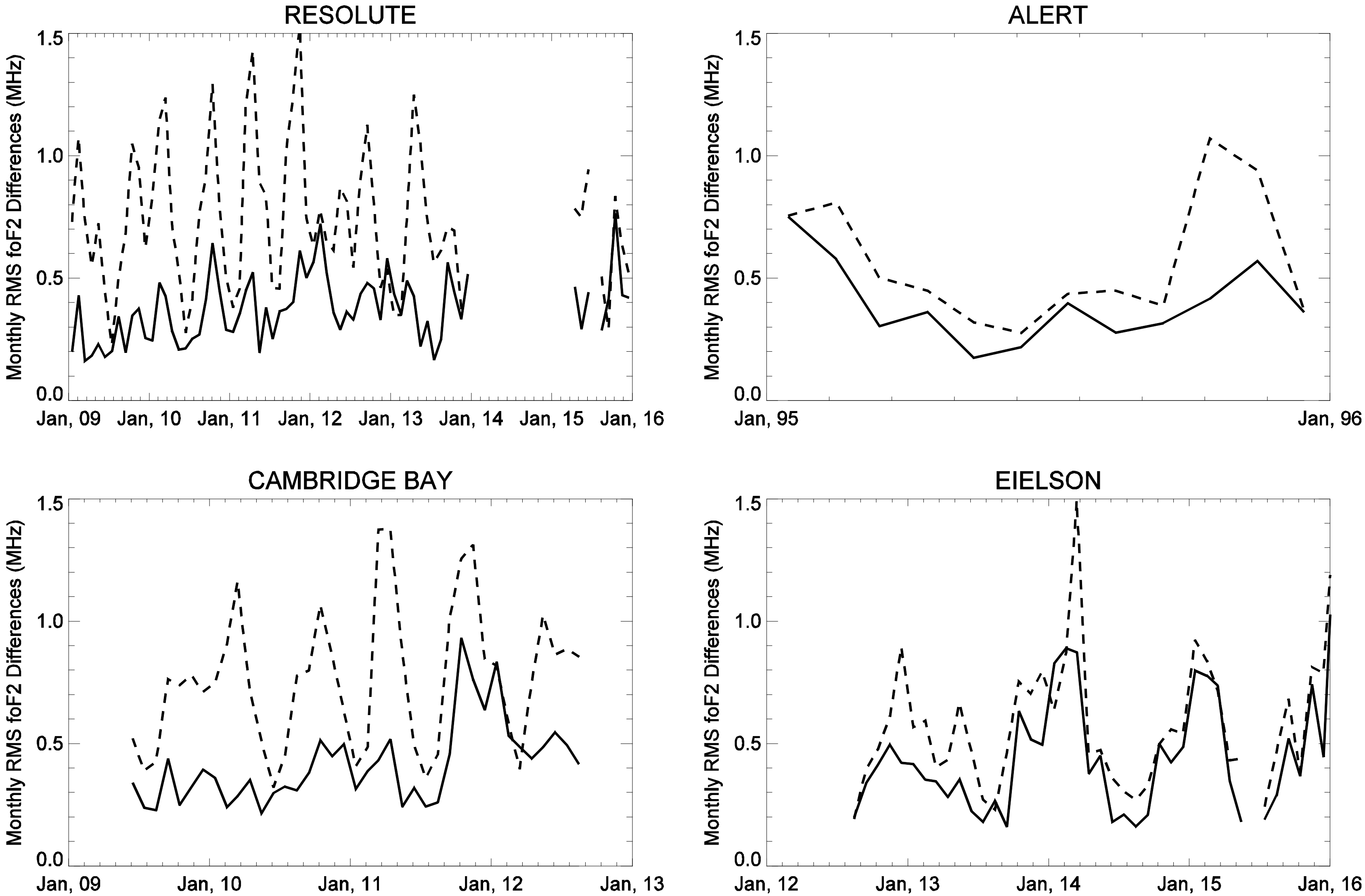


Resolute



Eielson

Validation: 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

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

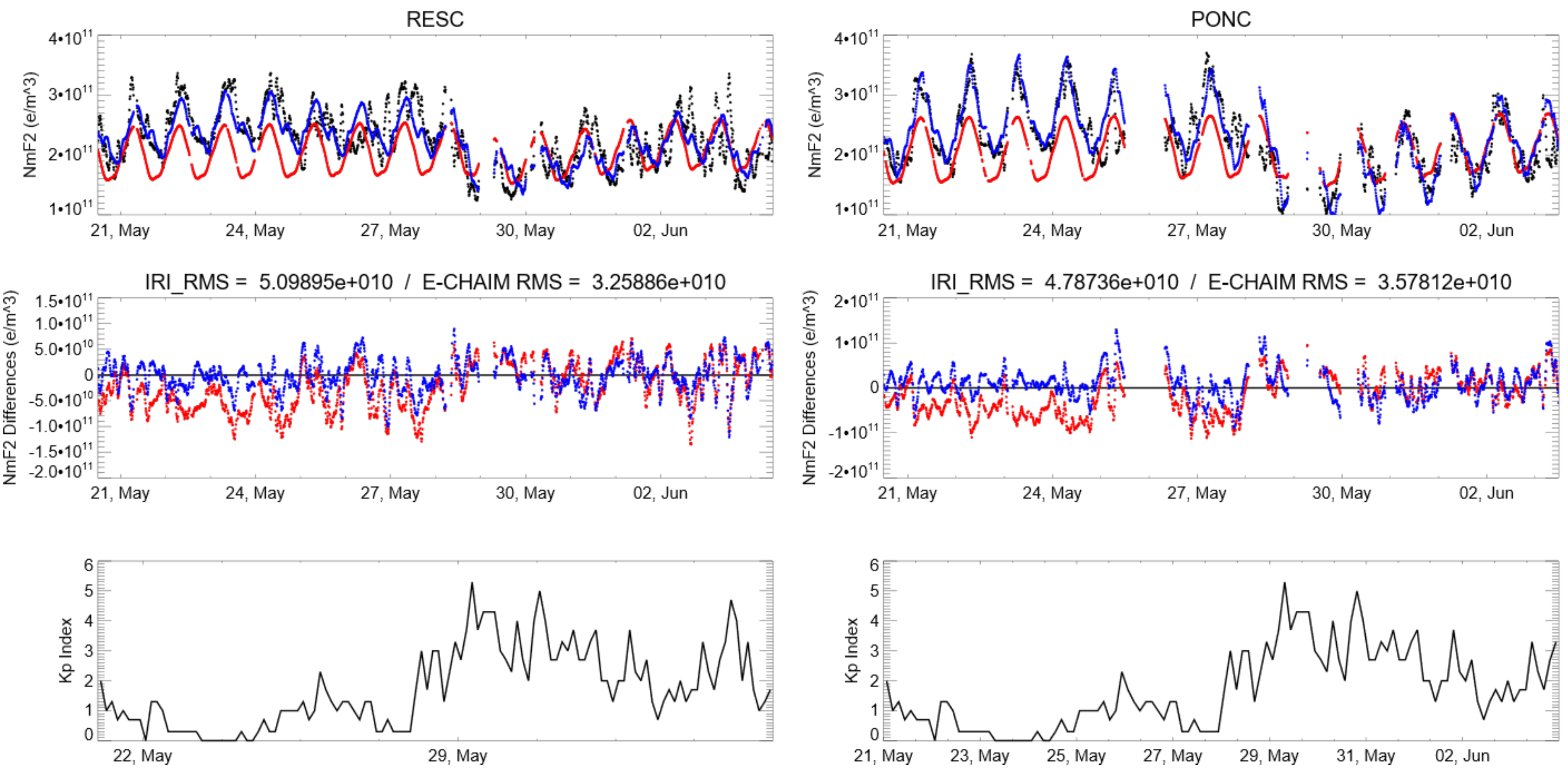
$$A_{lm}, B_{lm} = \sum_{d=1}^{3} \left(\alpha_{lm}\sin\theta + \beta_{lm}\cos\theta + (\gamma_{lm}\sin\theta + \delta_{lm}\cos\theta)\sqrt{F10.7}\right) G_d$$

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

$$\Gamma' = (1-\tau)[\Gamma_0 + \tau\cdot\Gamma_1 + \tau^2\cdot\Gamma_2 + \cdots]$$

$$\tau = 0.95, 0.75, 0.95$$

Evaluation: May 21 – June 5, 2010



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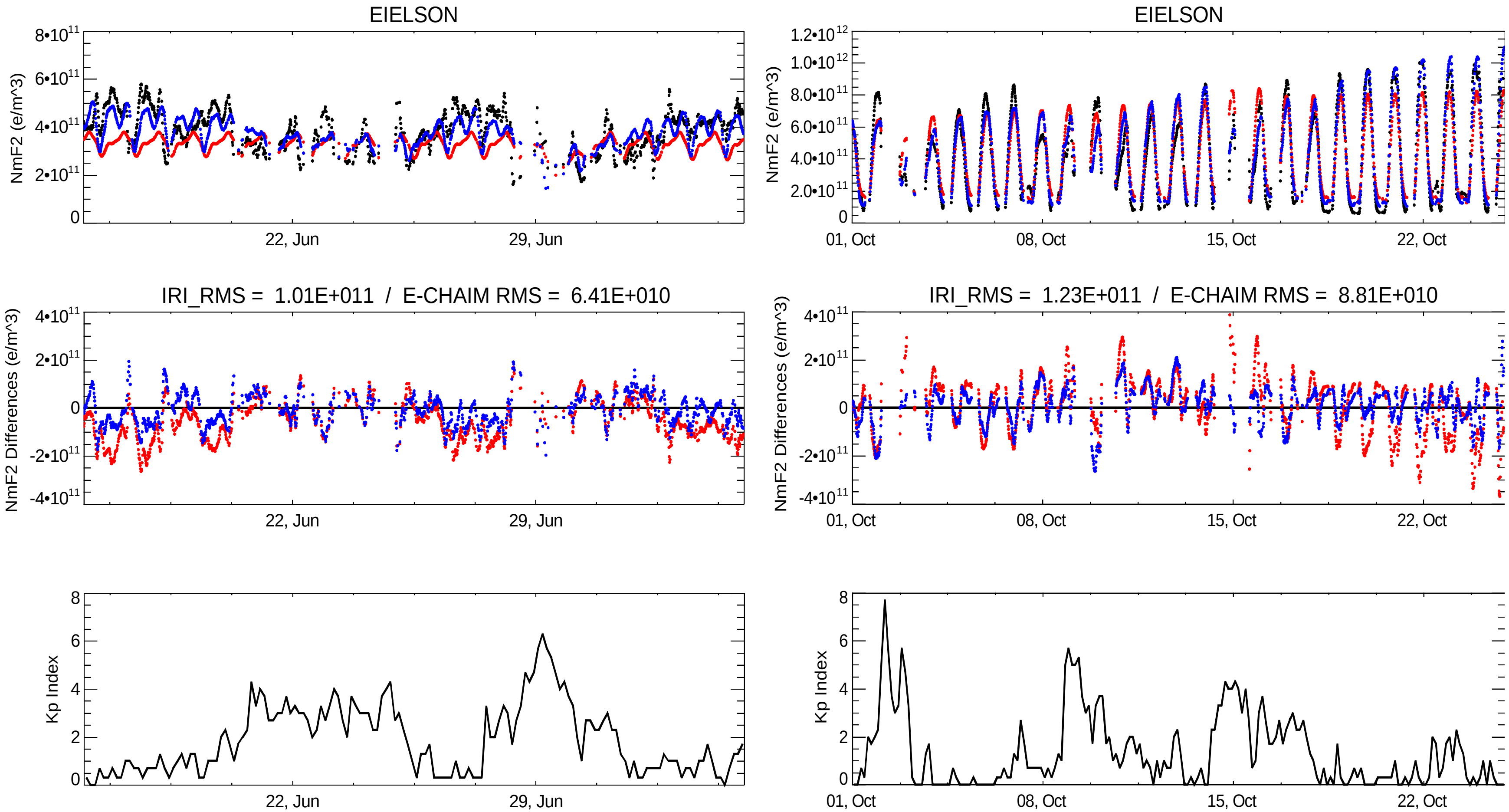

EIELSON
NmF2 (e/m^3)
8•10^11
6•10^11
4•10^11
2•10^11
0
22, Jun
29, Jun
EIELSON
1.2•10^12
1.0•10^12
8.0•10^11
6.0•10^11
4.0•10^11
2.0•10^11
01, Oct
08, Oct
15, Oct
22, Oct
IRI_RMS = 1.01E+011 / E-CHAIM RMS = 6.41E+010
NmF2 Differences (e/m^3)
4•10^11
2•10^11
-2•10^11
-4•10^11
IRI_RMS = 1.23E+011 / E-CHAIM RMS = 8.81E+010
Kp Index
8
6
4
2

Summary

- E-CHAIM constitutes a significant and universal improvement over the IRI in the representation of NmF2.
- Within the polar cap, the use of E-CHAIM constitutes an improvement over the IRI by over 1MHz, particularly during equinox periods.
- The use of the storm perturbation adjustment results in a 15-40% improvement over the climatological E-CHAIM model representation during storm periods.

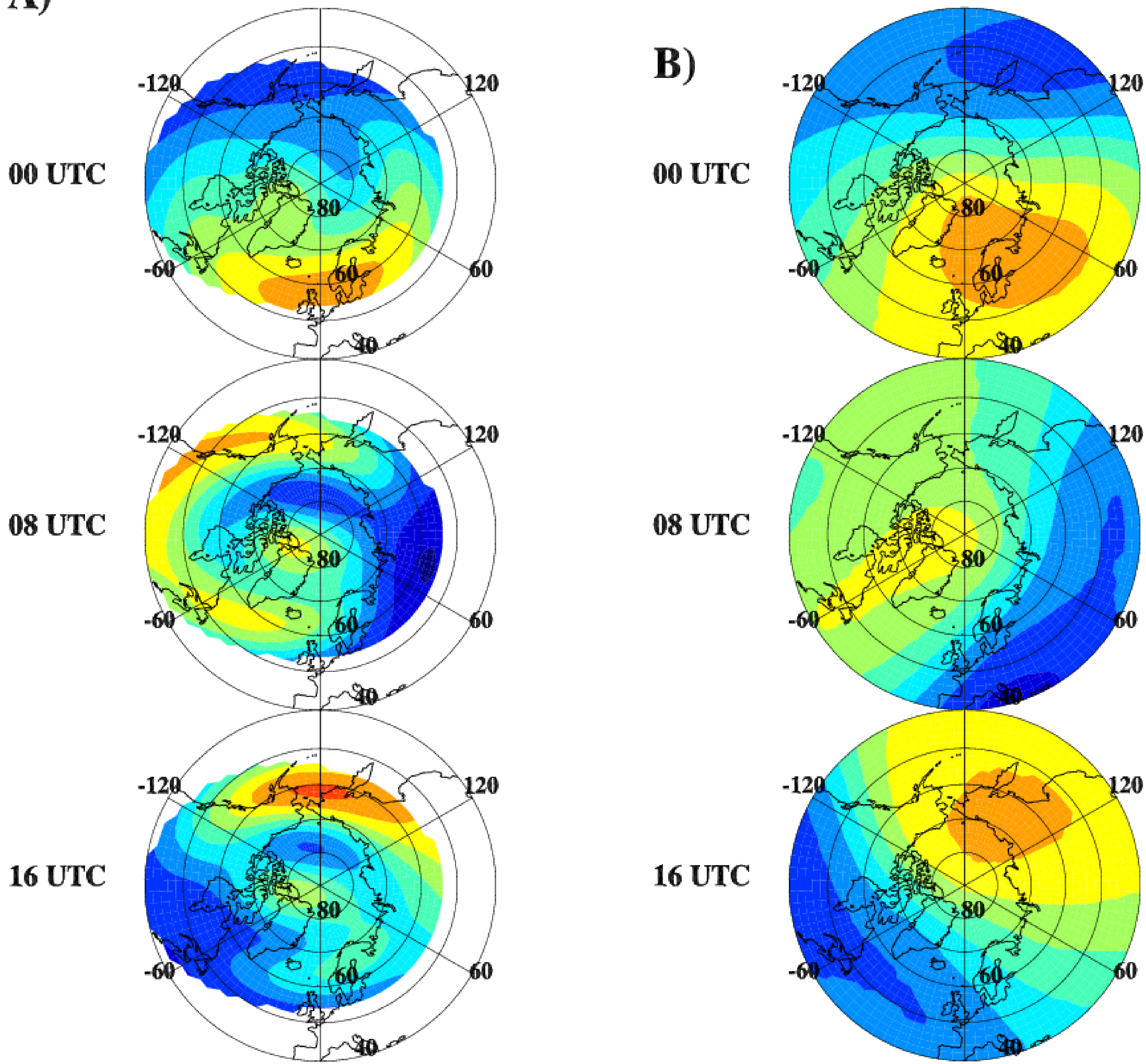
Current Status

- hmF2 and NmF2 models are complete.
- Topside model is complete.
- Error models for hmF2, NmF2, and topside electron density are complete.
- Fitting of bottomside climatological model is in progress.
- Bottomside perturbation model on the books.
- 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

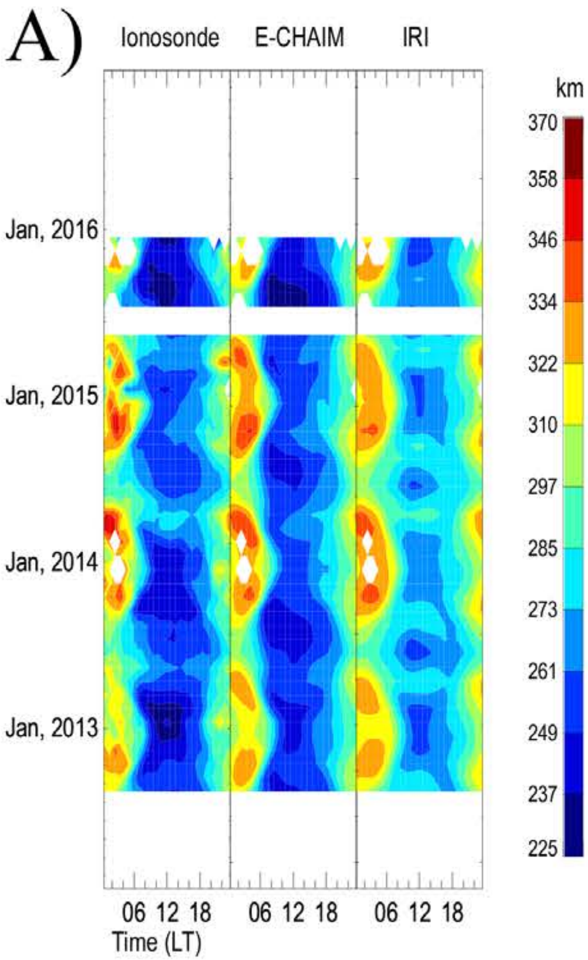
The Rest of the Model

hmF2

- Similar parameterization to NmF2 but with a F10.7^2.0 as the non-linear solar activity driver.
- No perturbation model has been developed yet: ionosonde data during storms is particularly questionable for hmF2 due to E-F valley conditions and absorption of the low-frequency portion of the profile.
- Spherical Cap expansion is limited to a 3-3 expansion. Spatial structure is nonetheless far more defined than that of the IRI.


A)
B)
00 UTC
08 UTC
16 UTC
-120
120
-60
60
80
60
40

hmF2: Complete



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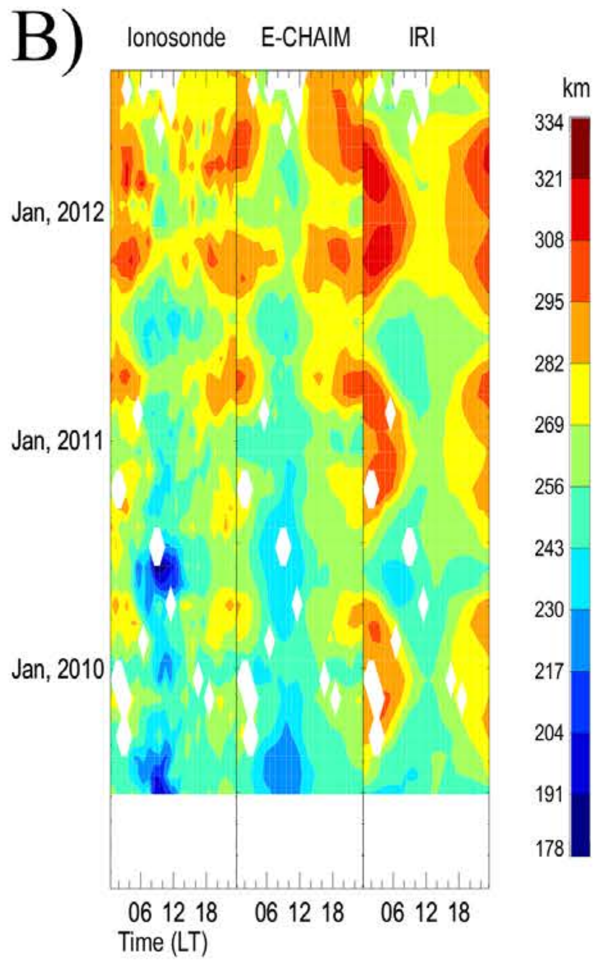
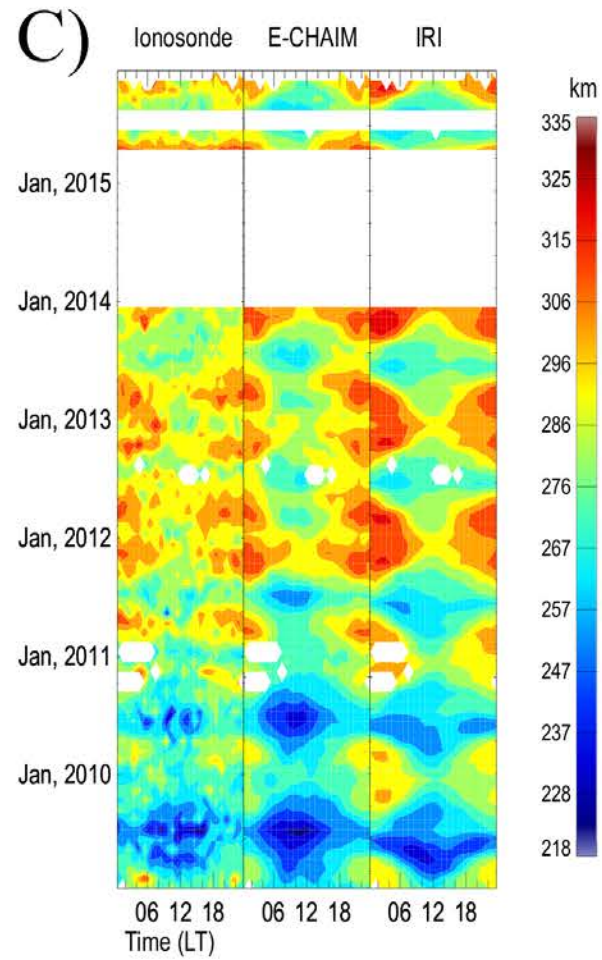


Cambridge Bay

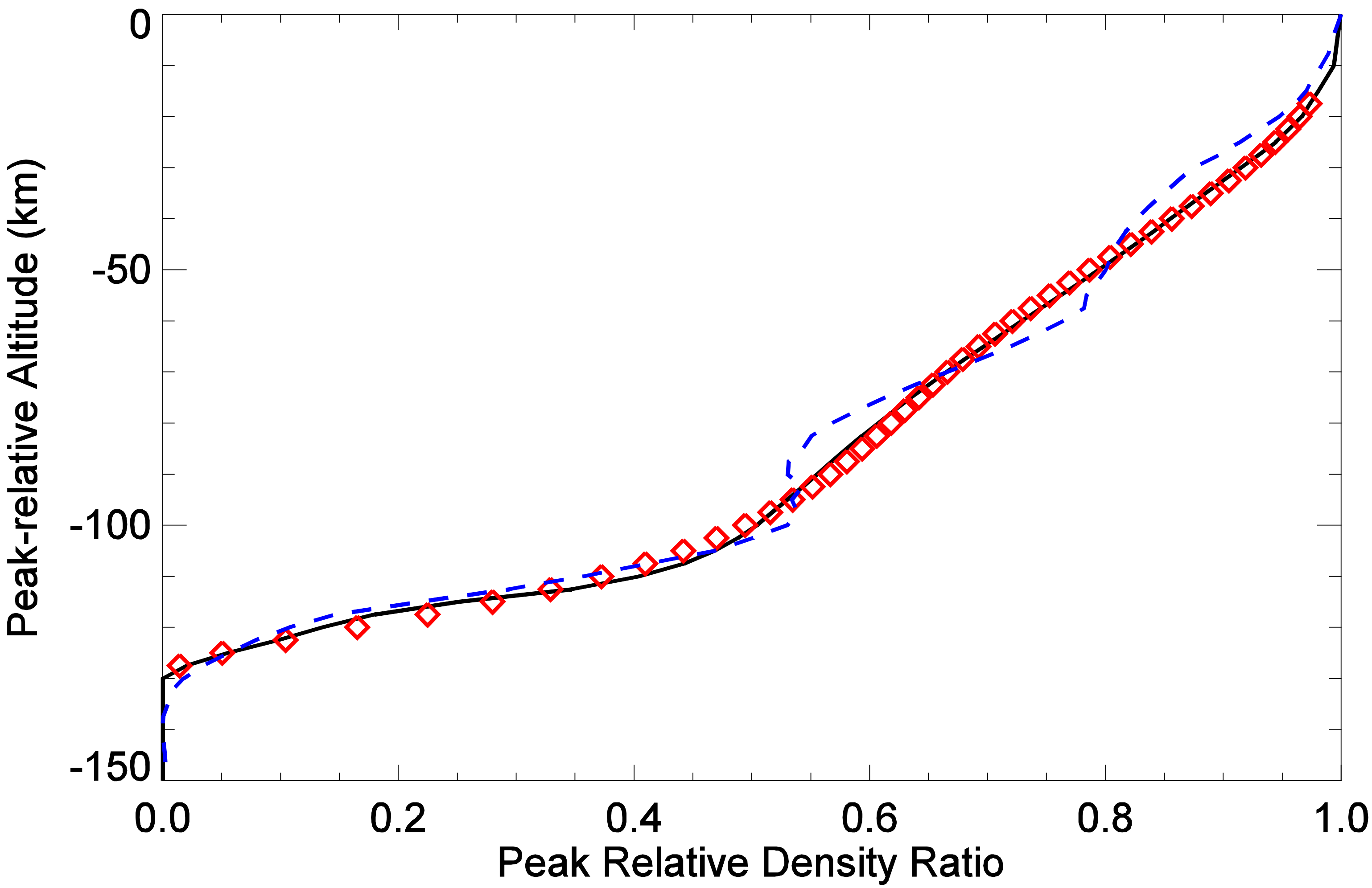


Resolute

Bottomside Parameterization

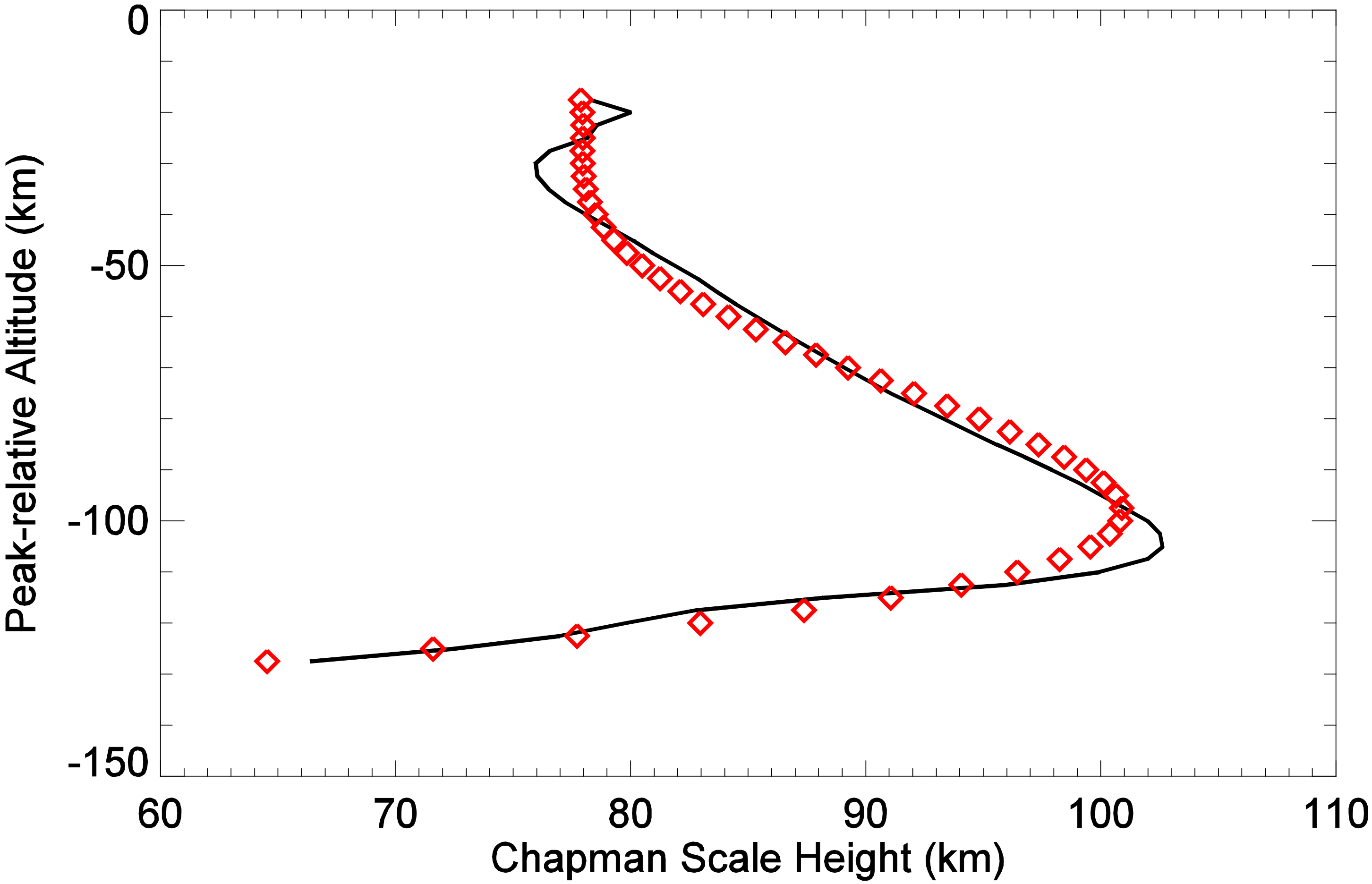
- Originally wanted to use Empirical Orthogonal Functions (EOFs) to represent the bottomside vertical structure of the E-CHAIM ionosphere, but E and F1 profile inflections are not sufficiently statistically important with respect to F-layer thickness variability.
- Also, EOFs are not explicitly differentiable, 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
0.0
0.2
0.4
0.6
0.8
1.0
Peak-relative Altitude (km)
Peak Relative Density Ratio

Scale Height



Topside

- Incoherent Scatter Radar, Topside Sounder, and Radio Occultation electron density profiles have been fitted to a semi-Epstein layer function (beginning with the NeQuick parameterization).
- Only the layer thickness will need to be modeled explicitly.
- This thickness is fitted to a spherical cap expansion in mag. lat and MLT with linear F10.7 flux and AE index driving terms.
- Solar zenith angle is included in the same manner as for NmF2 to help account for UT-dependant variabilities.

The NeQuick Model

- The NeQuick Topside Model is a semi-Epstein layer with varying scale height.

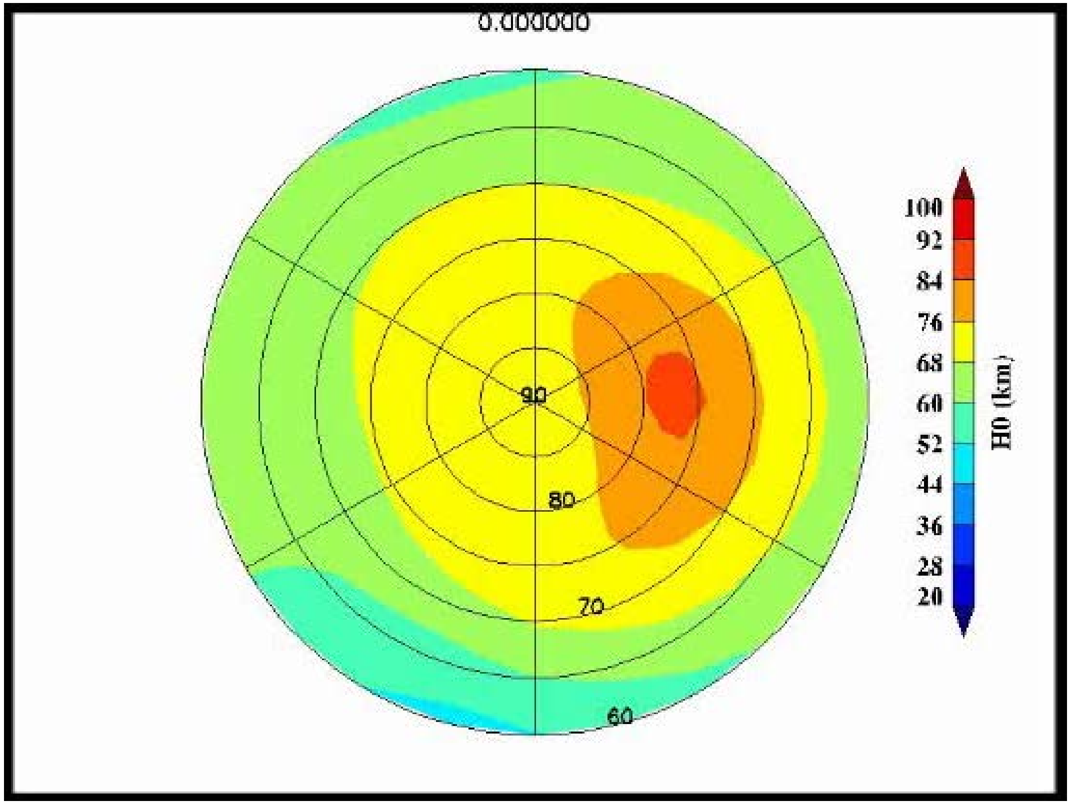
$$N(h) = \frac{4N_{max}}{(1 + \exp(z))^2} \exp(z)$$

$$z = \frac{h - hmF2}{H} \qquad \mathrm{H} = H_0 \left(\frac{1 + r \cdot g(h - hmF2)}{r \cdot H_0 + g(h - hmF2)} \right)$$

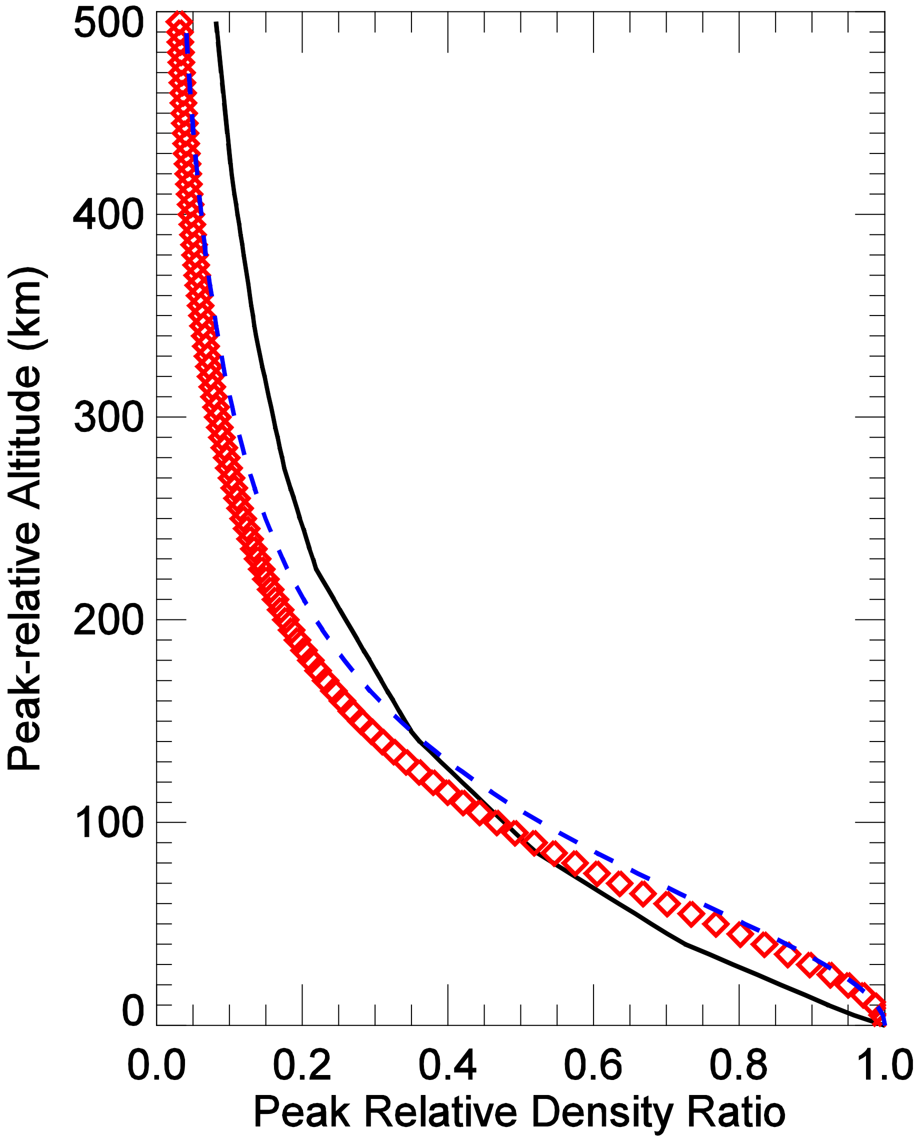
- Parameters r and g were selected as 100 and 0.125, respectively.
- There is no literature to back the reasoning for these r and g values.
- First attempt will just fit for H0. Further experiments will look at using either a linear H parameterization or adjusting r and g.

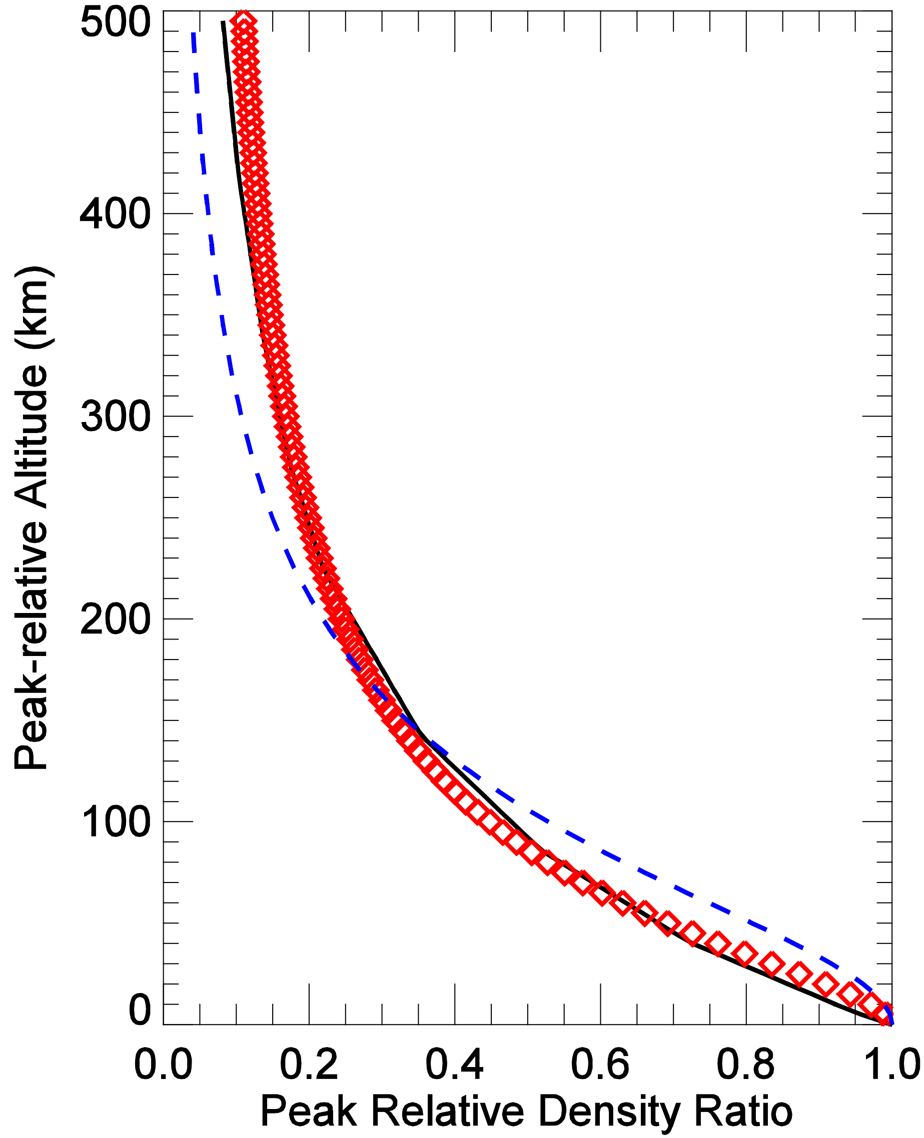
192 hours beginning May 30th, 2013

- 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.



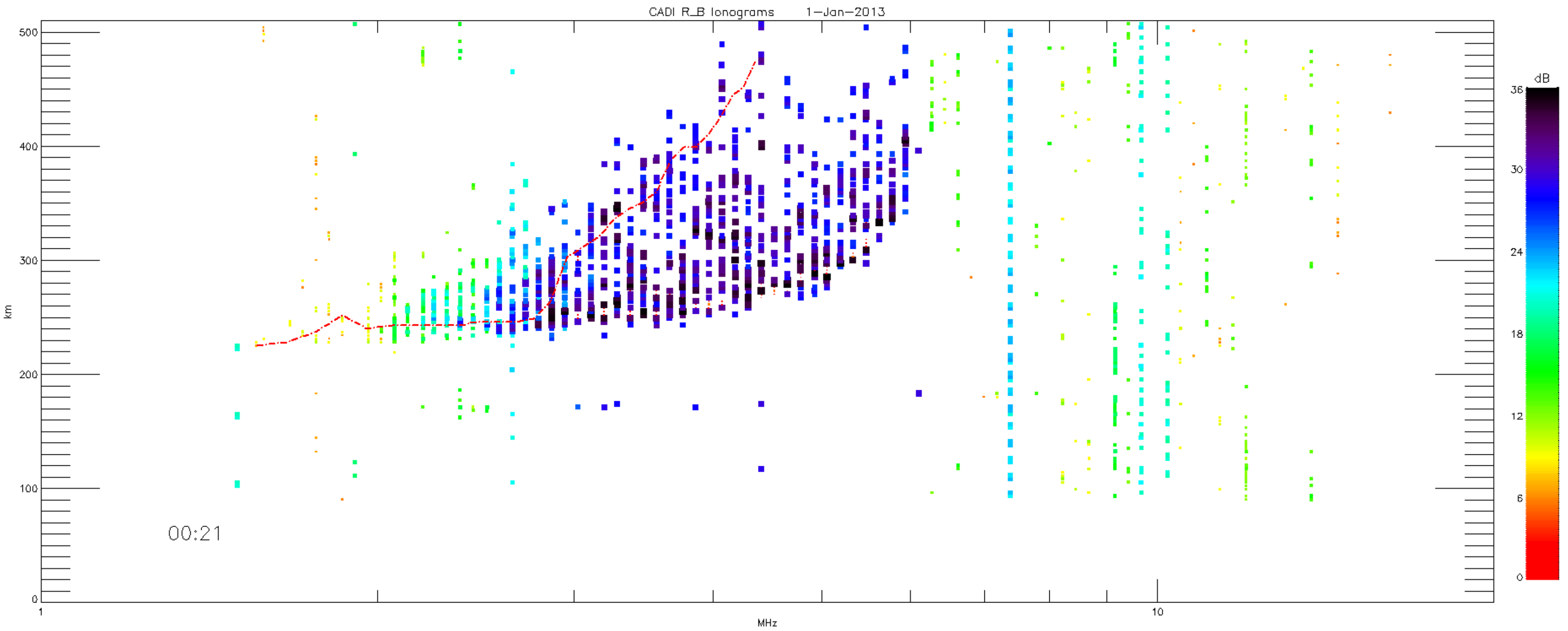
Other considerations:



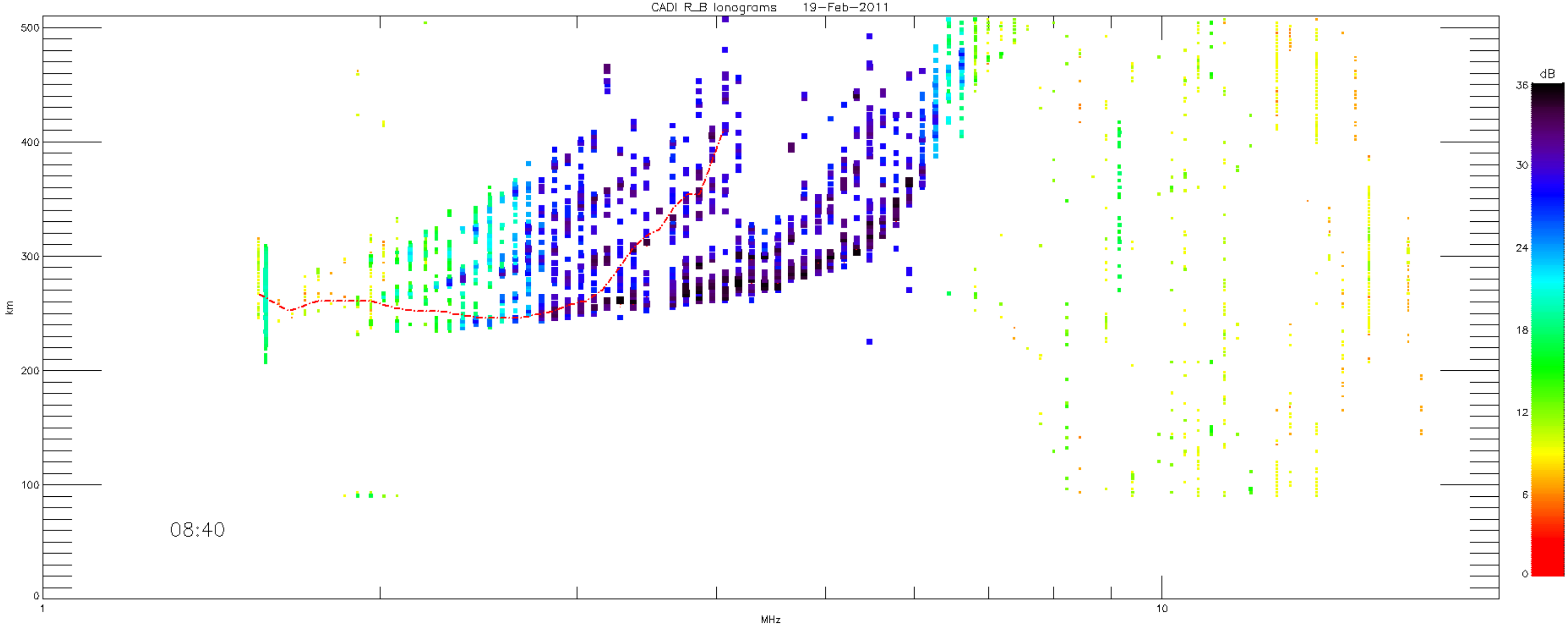


Conclusion

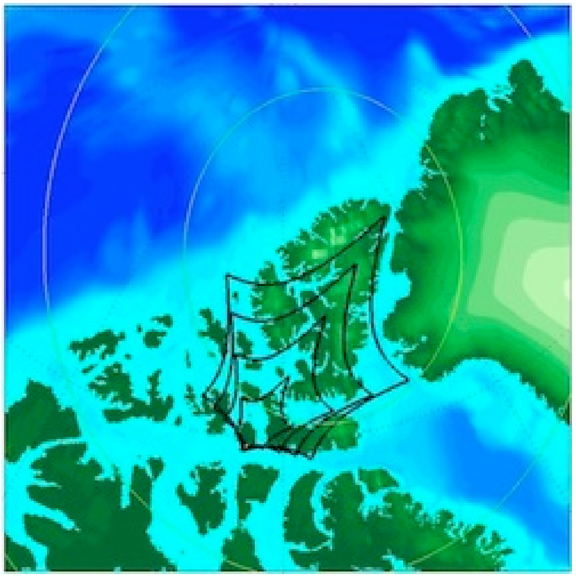
- The first two phases of the E-CHAIM model, namely the NmF2 and hmF2 parameterizations are now complete.
- NmF2 and hmF2 are demonstrating significant performance improvements over the use of the IRI.
- The bottomside and topside parameterization fitting well underway.

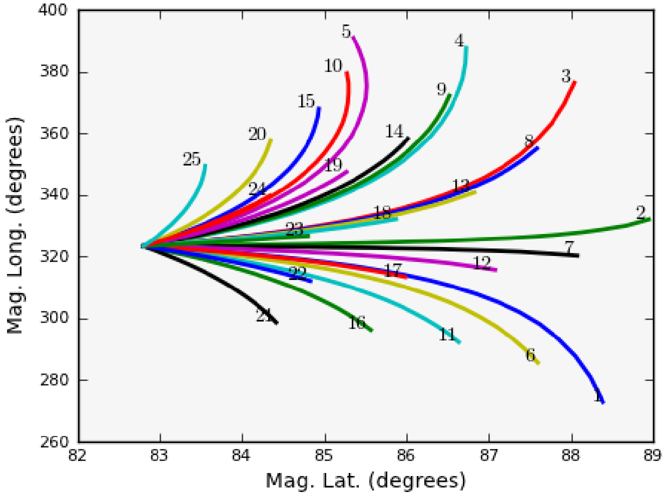


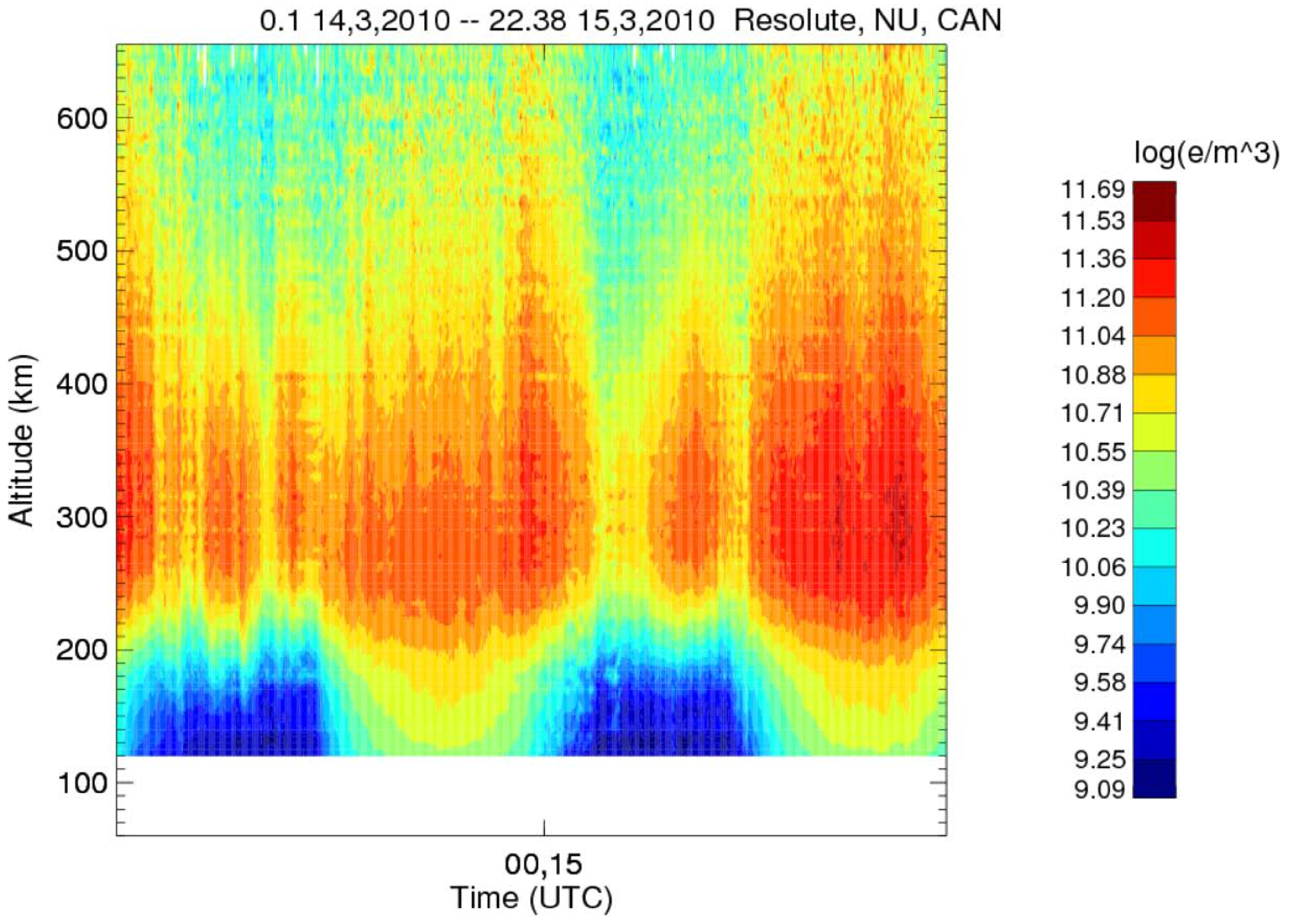
CADI R_B Ionograms 1-Jan-2013
500
400
300
200
100
0
km
1
10
MHz
00:21
dB
36
30
24
18
12
6
0


CADI R_B Ionograms 19-Feb-2011
km
MHz
dB
08:40
500
400
300
200
100
0
1
10
36
30
24
18
12
6
0

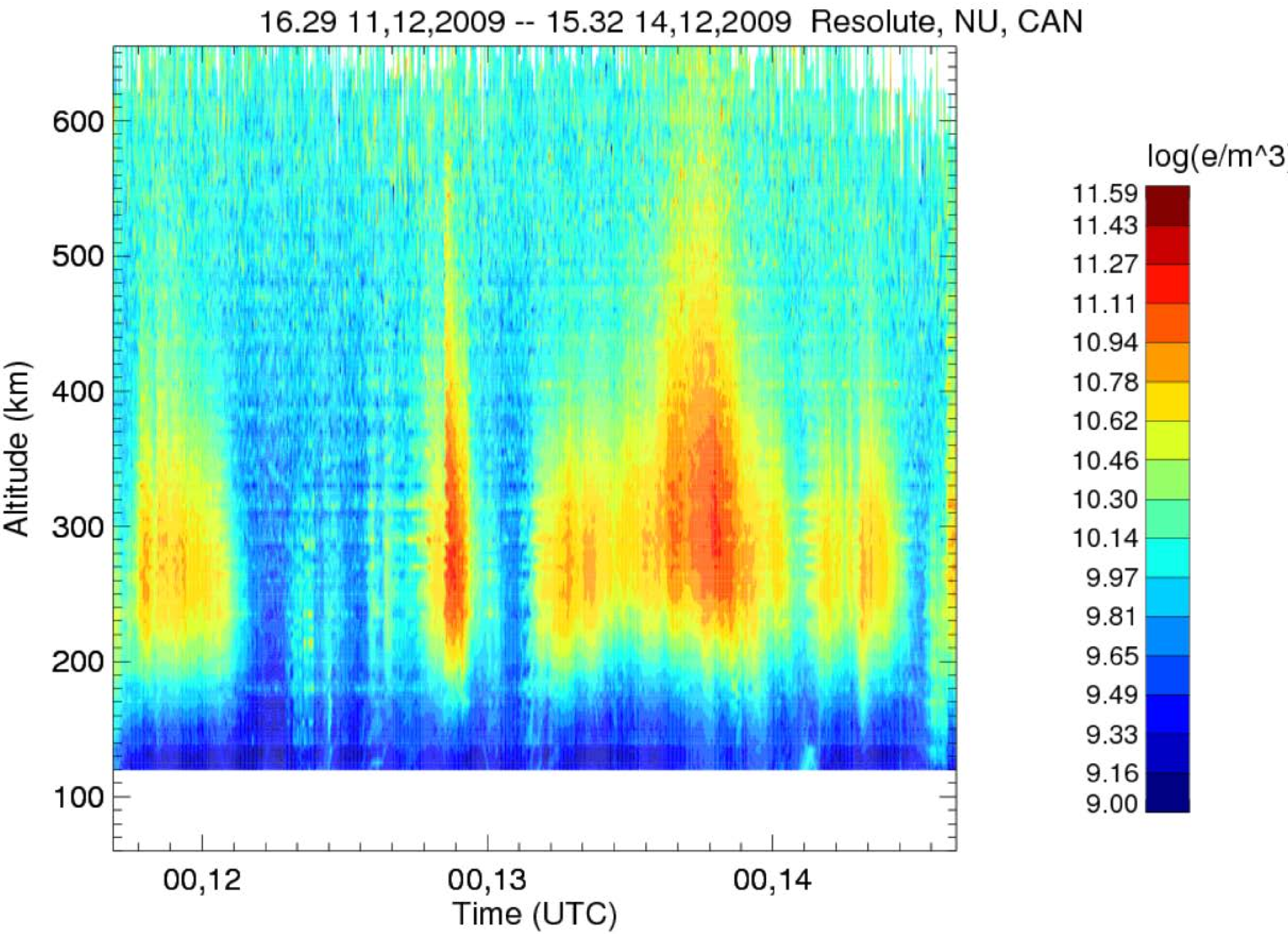
Incoherent Scatter Radar





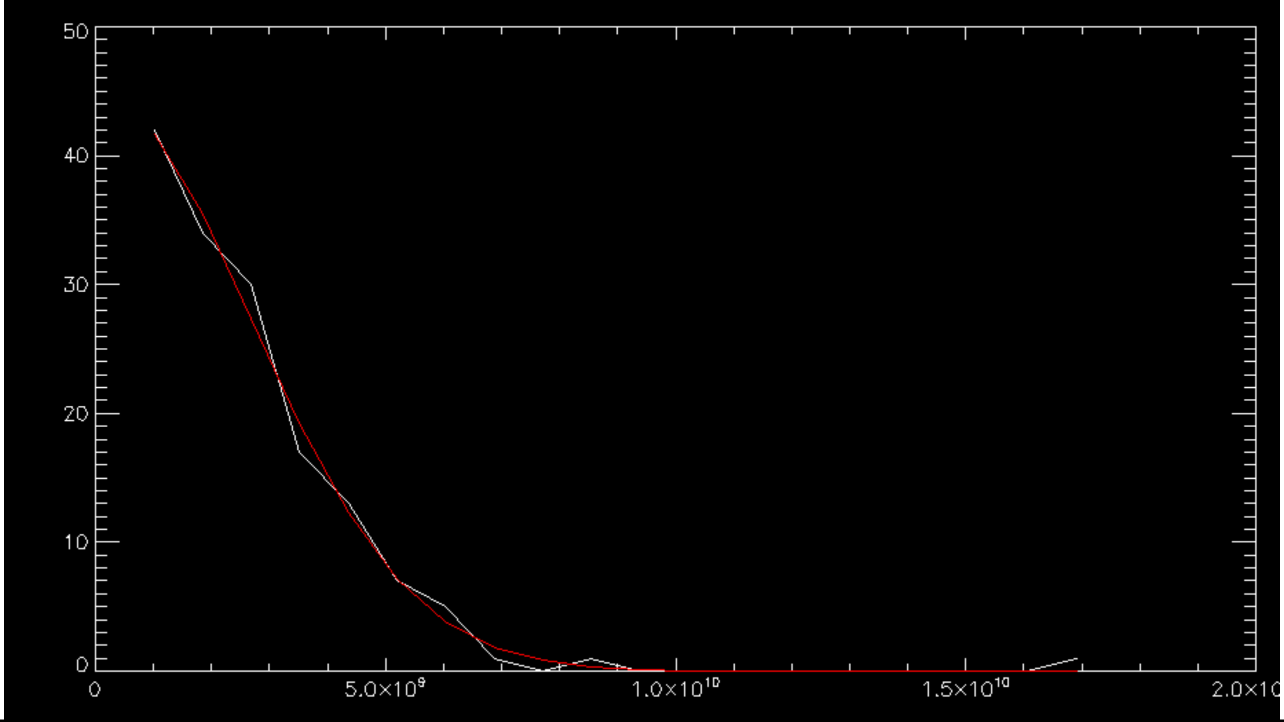


0.1 14,3,2010 -- 22.38 15,3,2010 Resolute, NU, CAN
Altitude (km)
600
500
400
300
200
100
00,15
Time (UTC)
log(e/m^3)
11.69
11.53
11.36
11.20
11.04
10.88
10.71
10.55
10.39
10.23
10.06
9.90
9.74
9.58
9.41
9.25
9.09



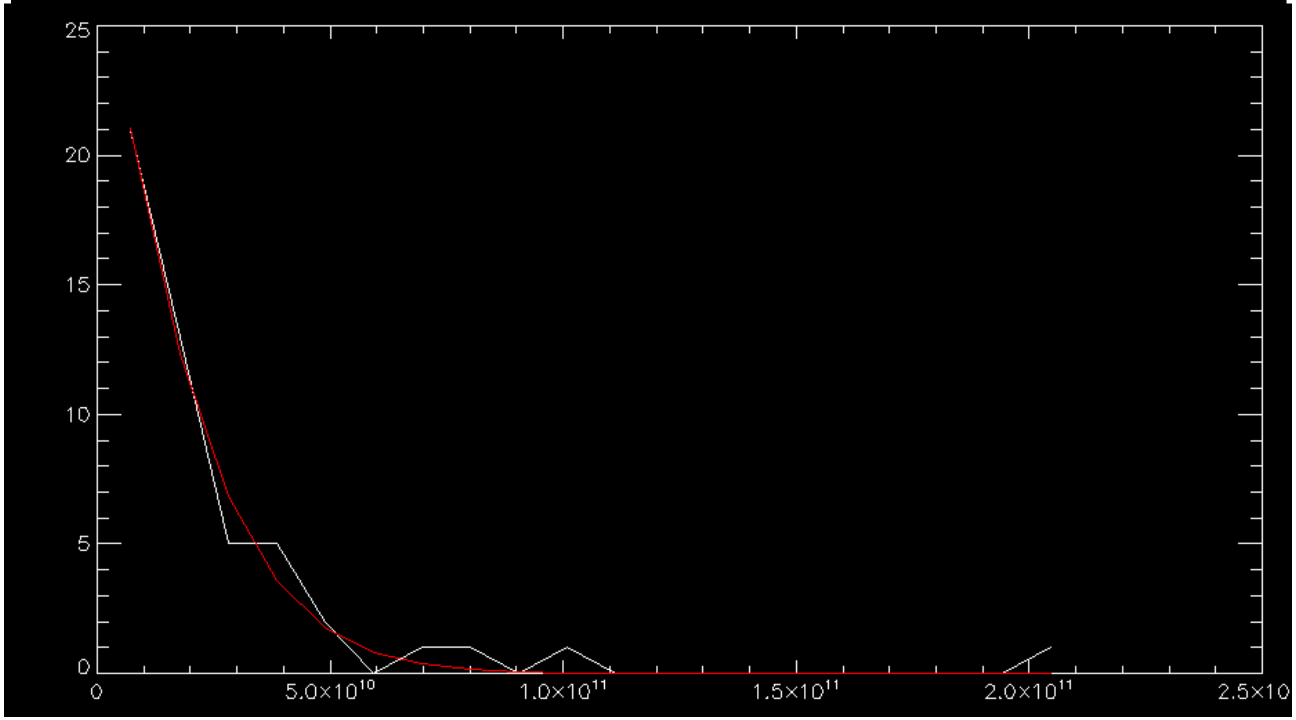
16.29 11,12,2009 -- 15.32 14,12,2009 Resolute, NU, CAN
Altitude (km)
600
500
400
300
200
100
00,12
00,13
00,14
Time (UTC)
log(e/m^3)
11.59
11.43
11.27
11.11
10.94
10.78
10.62
10.46
10.30
10.14
9.97
9.81
9.65
9.49
9.33
9.16
9.00

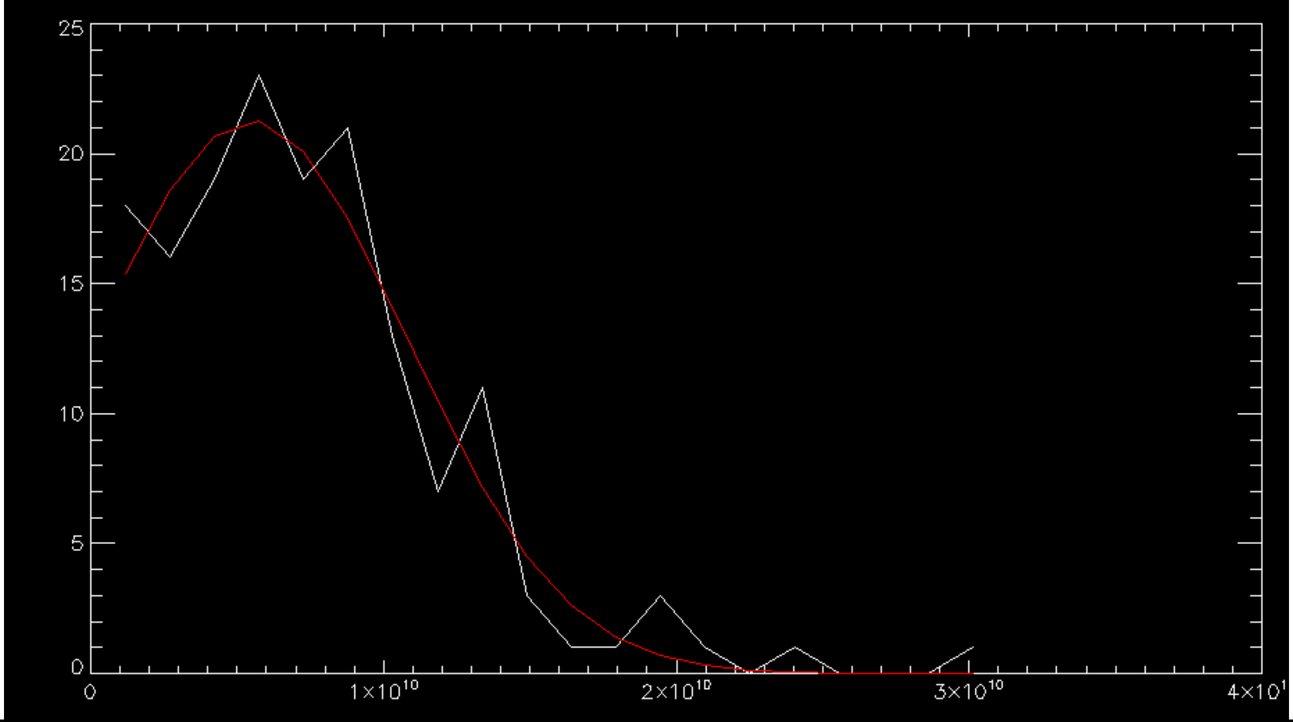
165 km

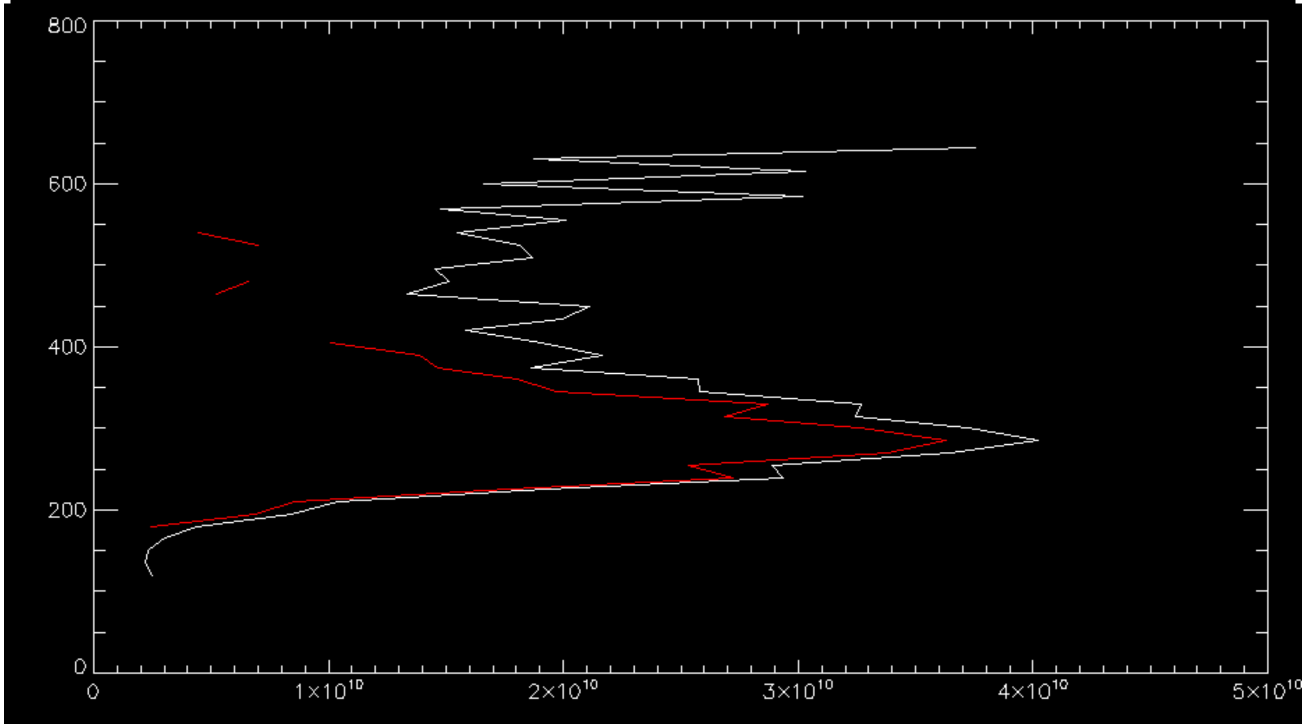


9:30 UTC
Jan 8th, 2011

585 km

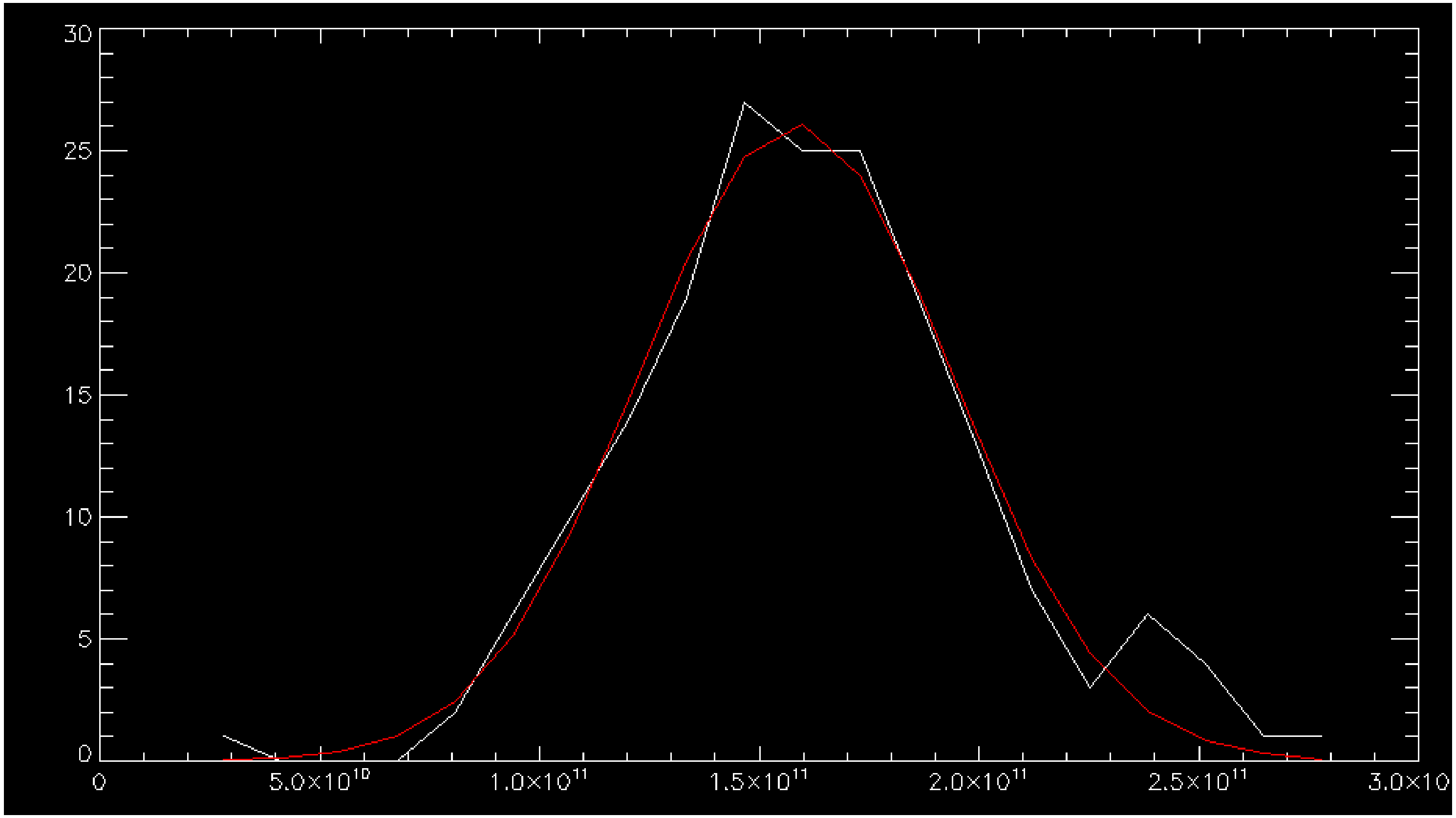




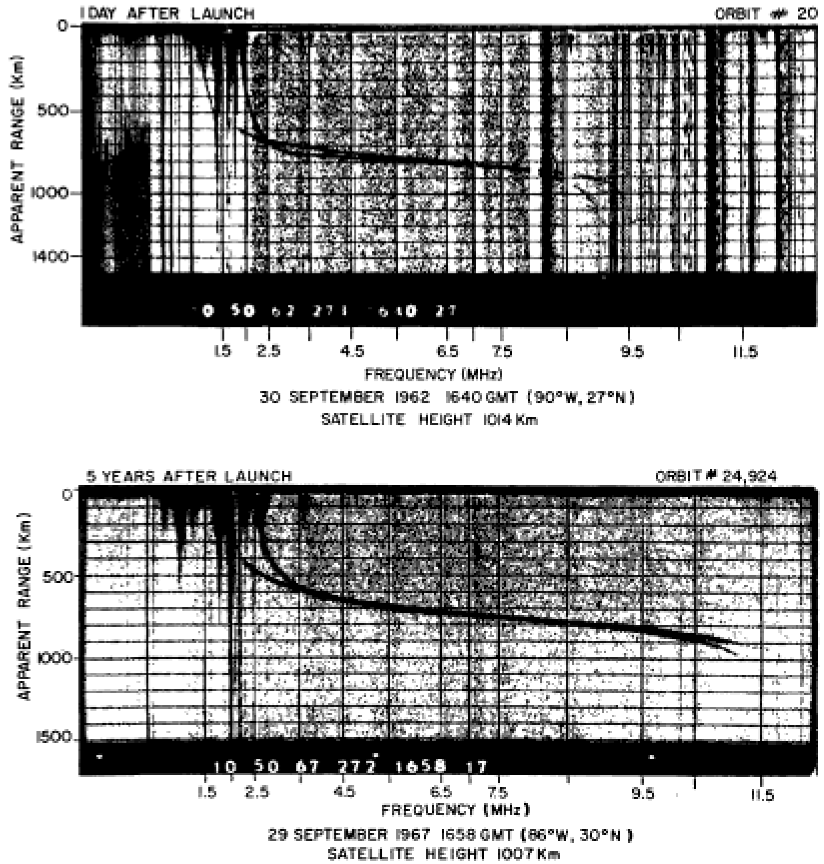


9:30 UTC
Jan 8th, 2011

300 km



Data: Topside Sounder



ALOUETTE I IONOGRAMS

Data: Radio Occultation

- Use data from CHAMP, GRACE, and COSMIC (ePOP for validation)