OPAC 4
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Impact Of The Ionosphere On GNSS Radio Occultation Retrievals

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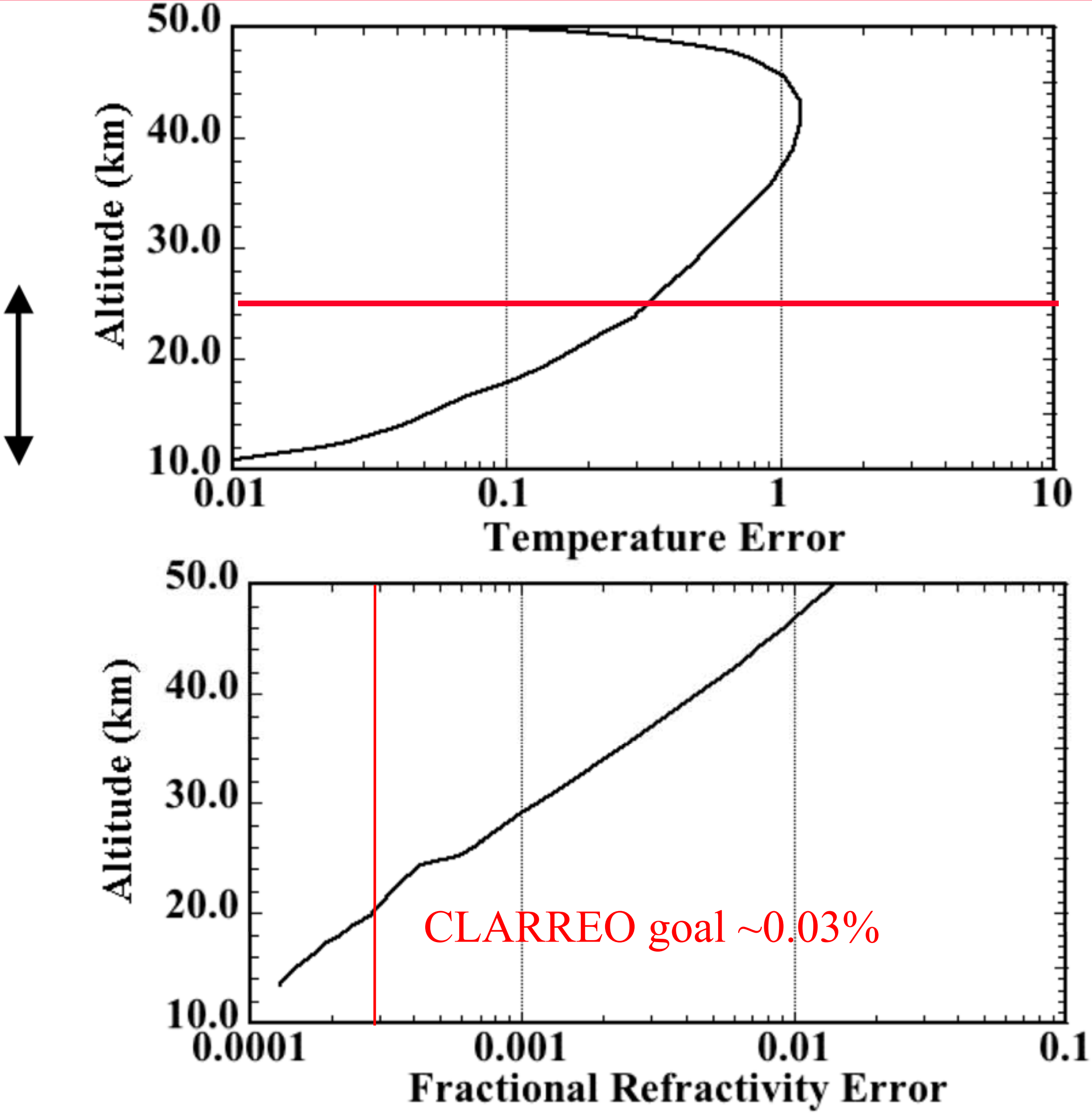
Outline

1. **Characterization**
   - **Where I suggest that standard ionospheric correction algorithm is inadequate**
2. **Mitigation**
   - **Where I review techniques that go beyond the standard**
3. **Analysis**
4. **Summary and Future Work**

Characterization

Magnitude Of The Error



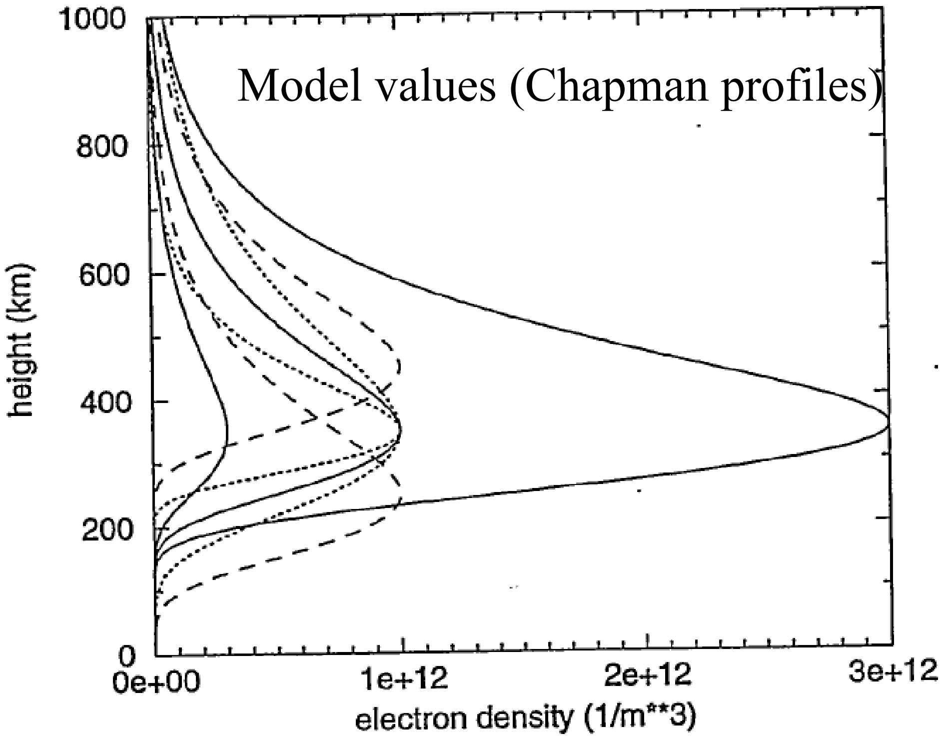
Method: ray-trace signal through a model ionosphere

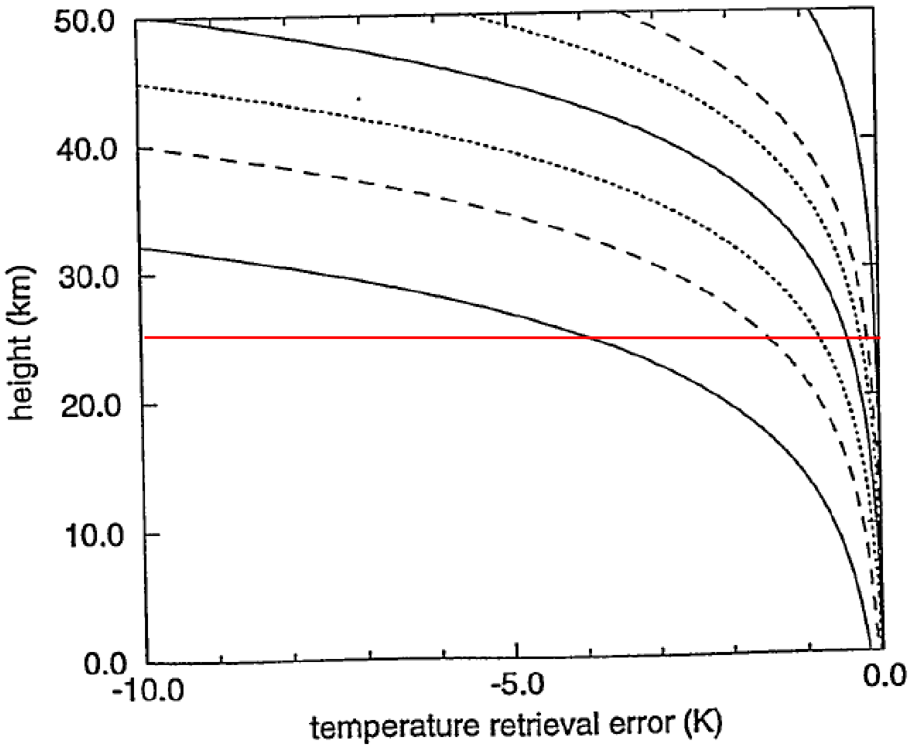
From the solar maximum simulation of Kursinski et al. JGR, 1997

Below 10 km, iono errors remain negligible

Error is too large by factor of 2-3

Magnitude Of The Error





From Gorbunov et al., 2006
"Space Refractive Tomography…"
MPI Report 210

Establishing a climate benchmark for CLARREO

"…2 a : a point of reference from which measurements may be made by something that serves as a standard by which others may be measured or judged …"

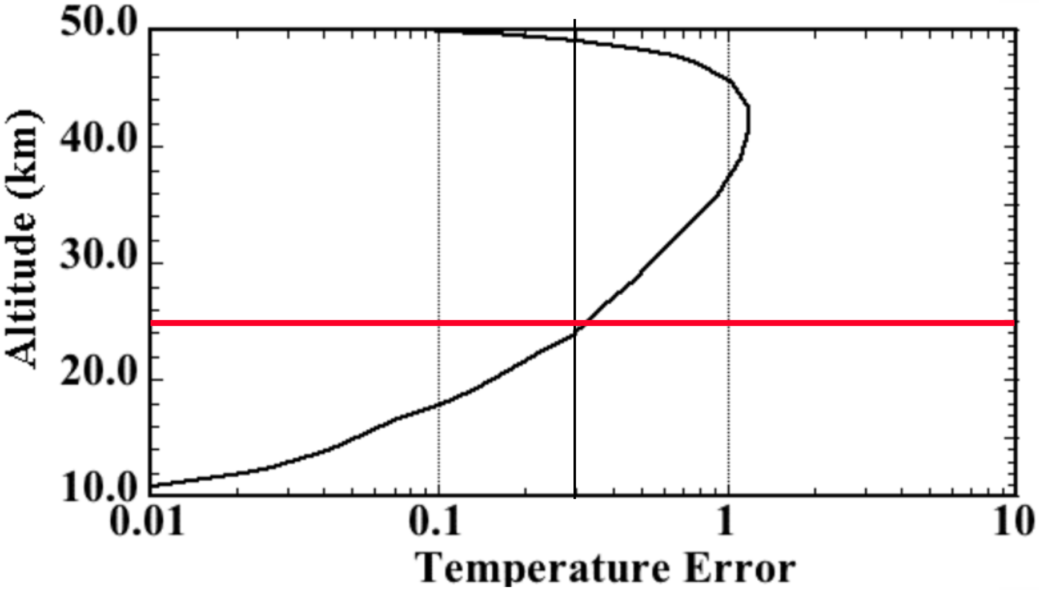
- **Documented absolute accuracy**
  - **Methods for establishing accuracy must be documented and widely accepted**
- **Accuracy standard based on SI-traceability**
  - **Systematic errors assessed by comparison to independent observations**
- **Error analysis**
  - **There will not be an independent measurement of exactly the same quantity**
- **Ionospheric biases will break SI-traceability unless ionosphere mitigation approaches have sufficient margin such that residual biases are well below requirements**
  - **"Unknown unknowns" are likely**

Why Is More Work Needed?

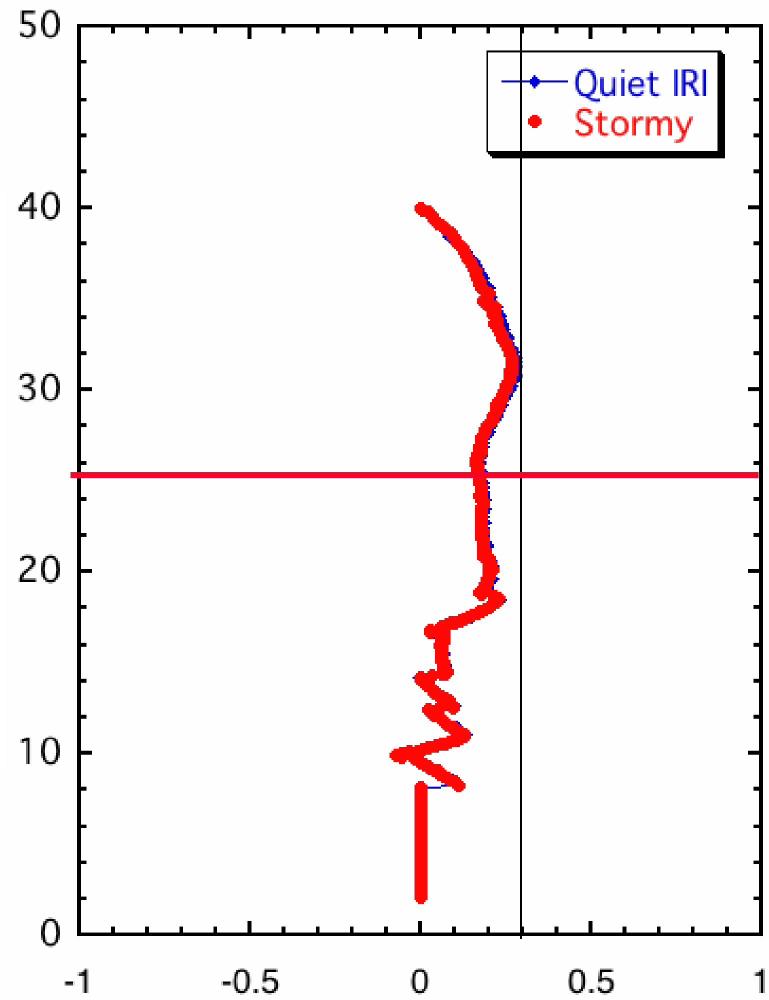
- Ionosphere is highly variable with solar cycle, with local time, and with geomagnetic activity
- Residual biases in temperature and refractivity at ~20 km exceed our objectives (e.g. CLARREO)
  - Daytime solar maximum, and possibly terminator
- Recent "technology developments" is an opportunity
  - Assimilative space weather models
  - Global ionospheric monitoring networks (ground and space based)
  - "Improved" Abel retrievals
  - Theoretical developments (Syndergaard, 2000 …)

Results (2007) Using International Reference Ionosphere

Result from Kursinski et al., JGR 1997



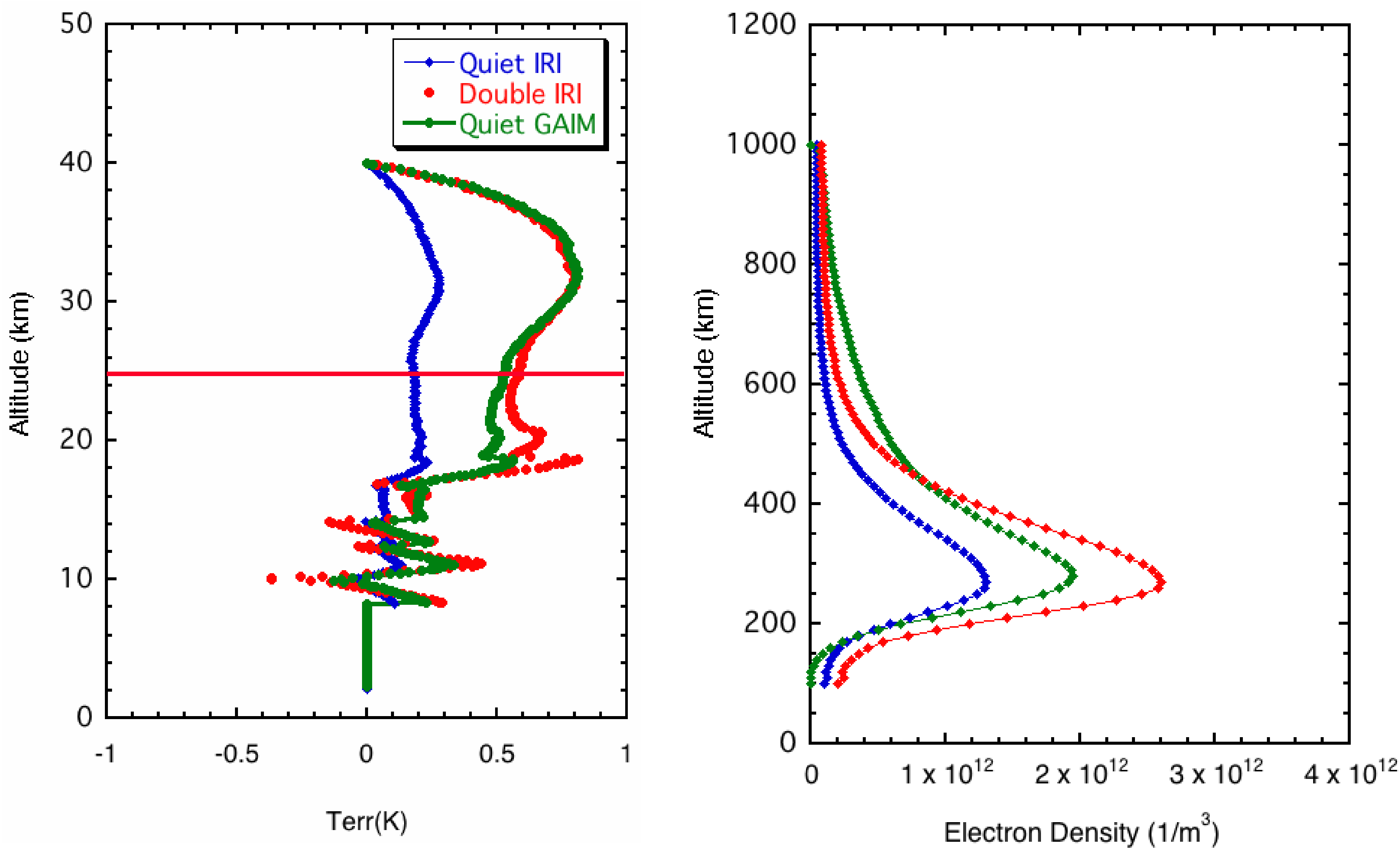
2D ray-trace



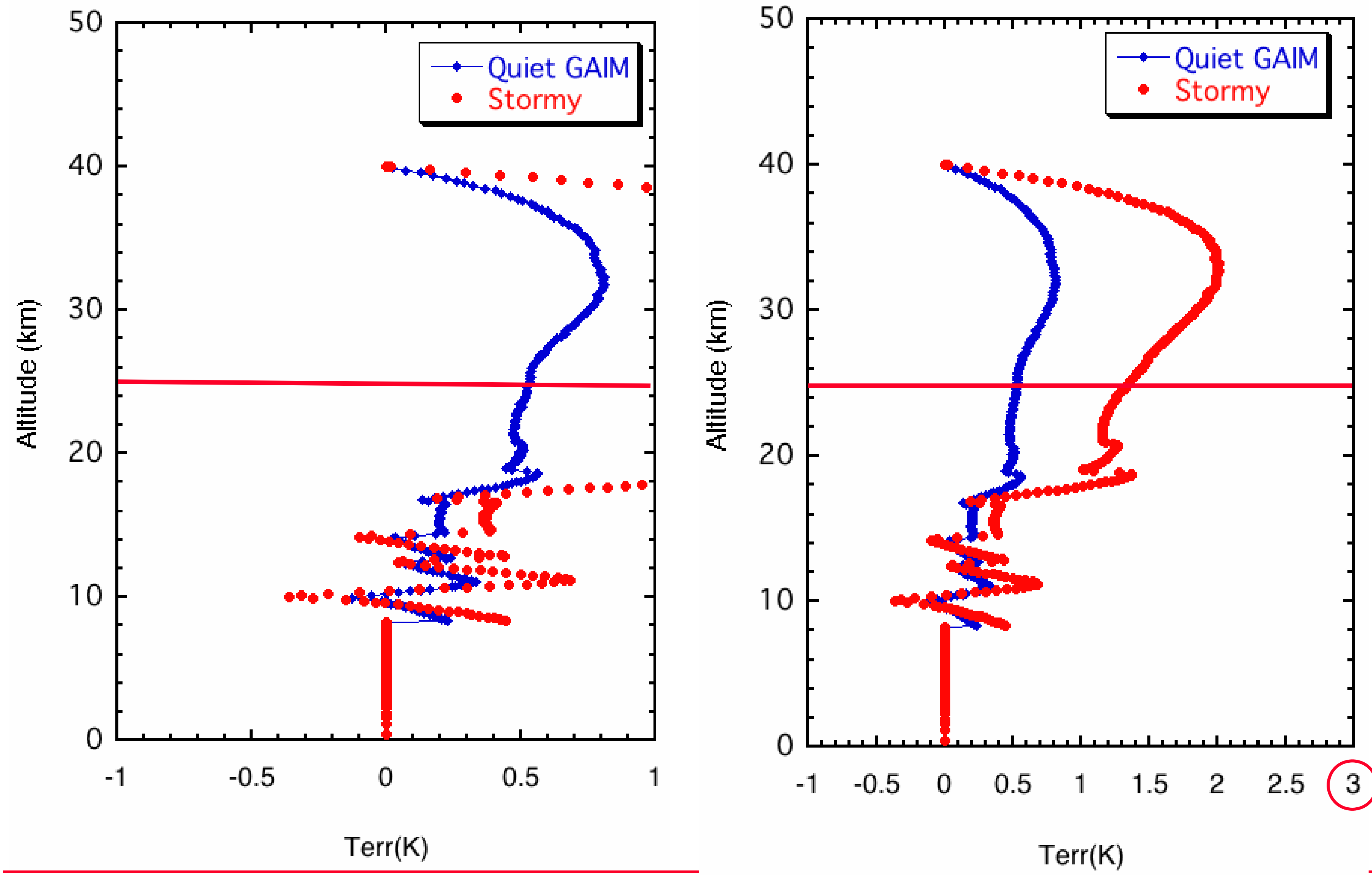
IRI more realistic than Chapman layers
Incorporates horizontal inhomogeneity

3D ray-trace

Error Vs. Electron Density



Assimilative Model Case (GAIM)

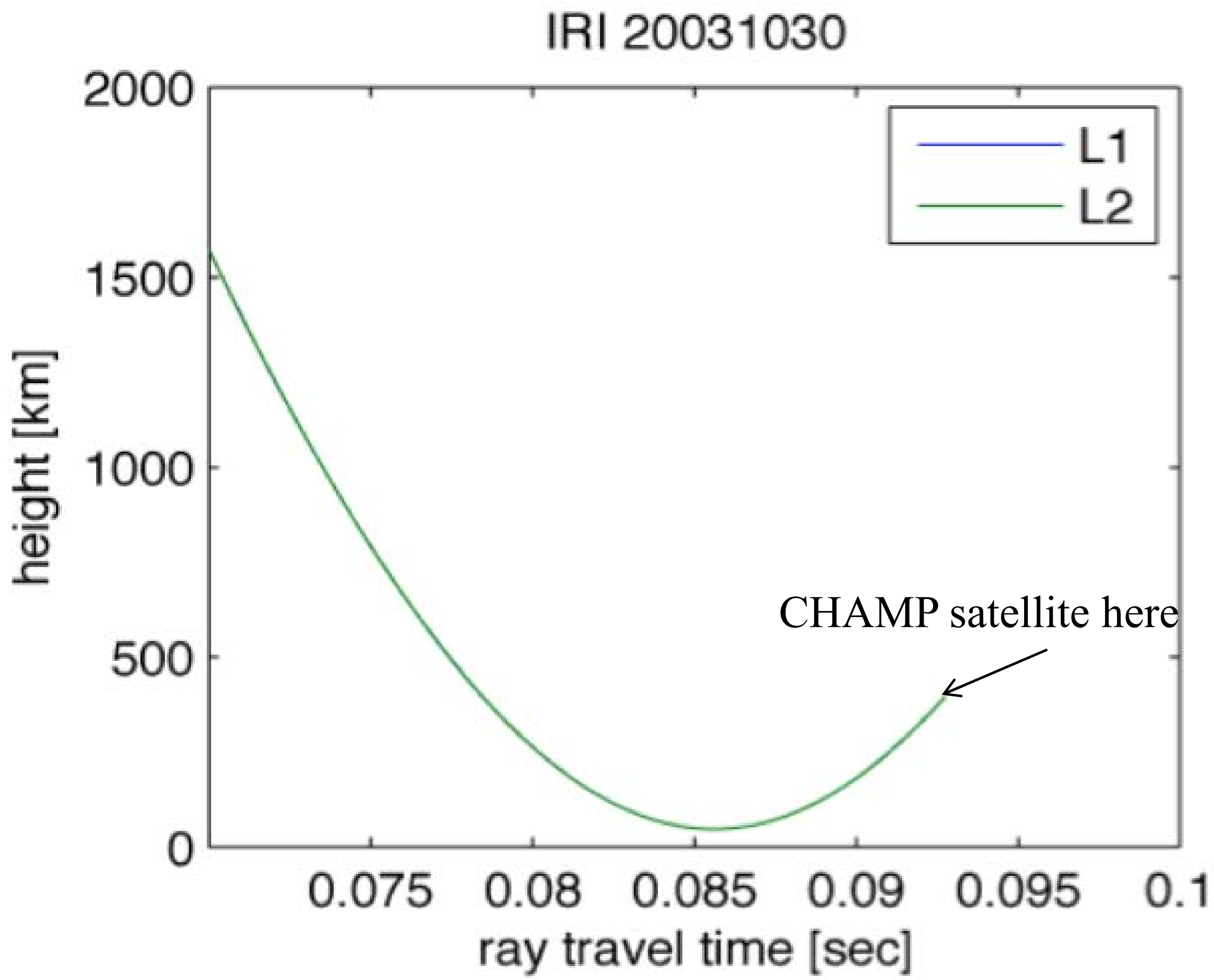


Conclusions – Characterization

- New simulation results are consistent with past work using "climatological" models of ionospheric refraction
- Realistic electron density fields (spherical asymmetry) predict significant daytime errors using 3D ray tracing
  - Up to ~0.5 K near solar maximum daytime at 25 km for quiet conditions
- For climate monitoring, improvements over standard bending angle correction should be implemented
  - Different centers should implement different methods

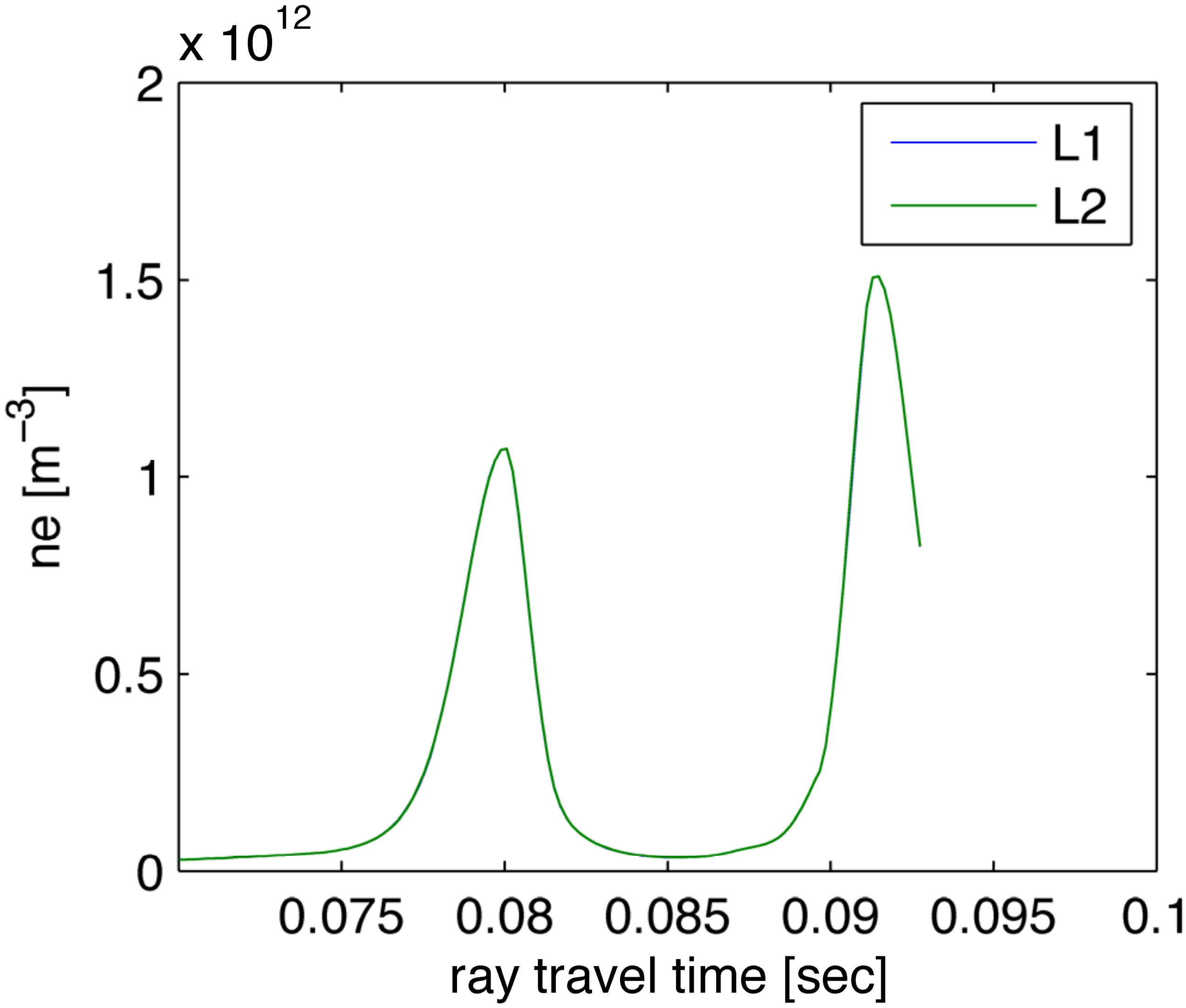
3D Ray Tracing: Detailed Results

Reference

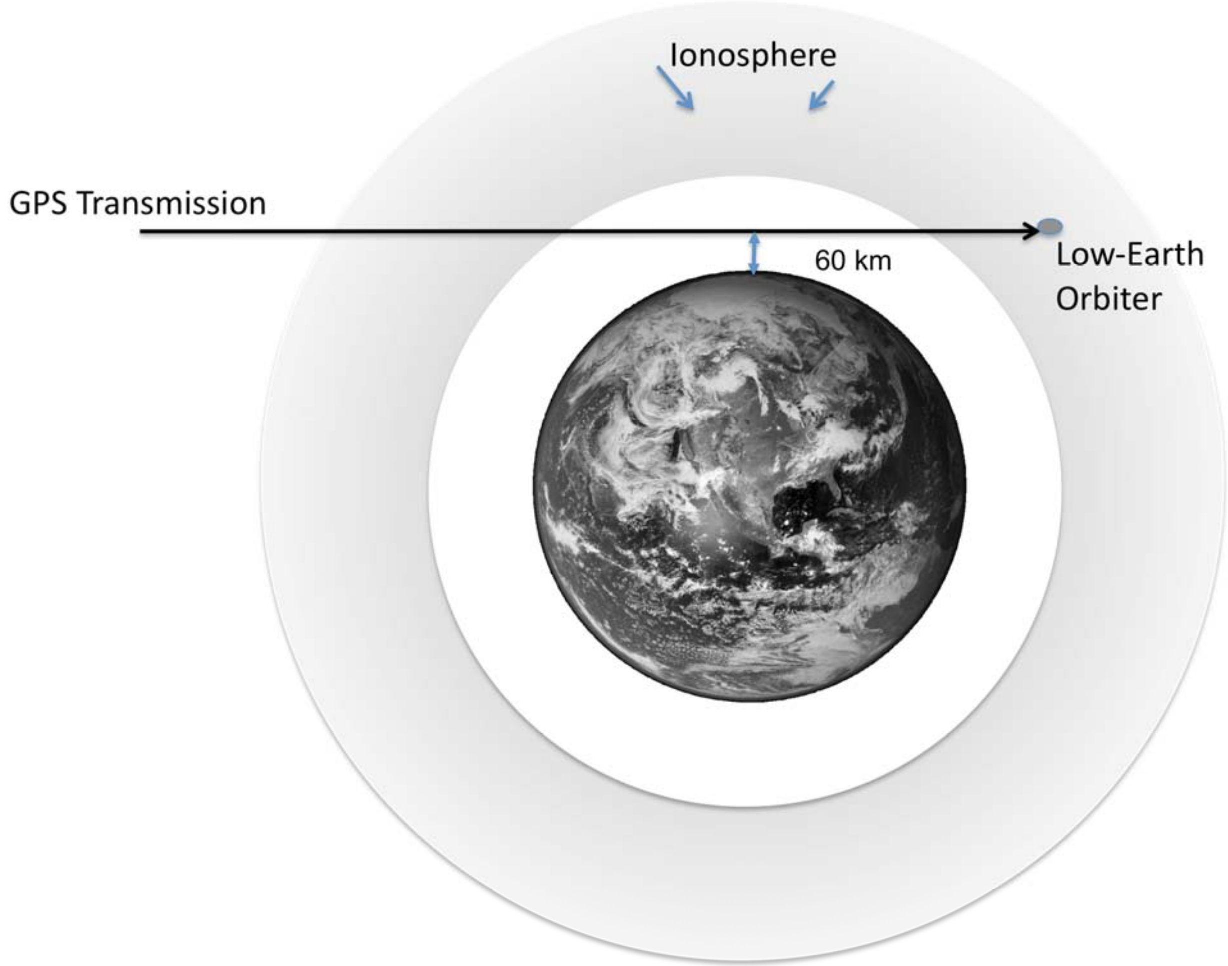


Satellite track is in daytime, over mid-latitude North America

Electron Density Along Raypath

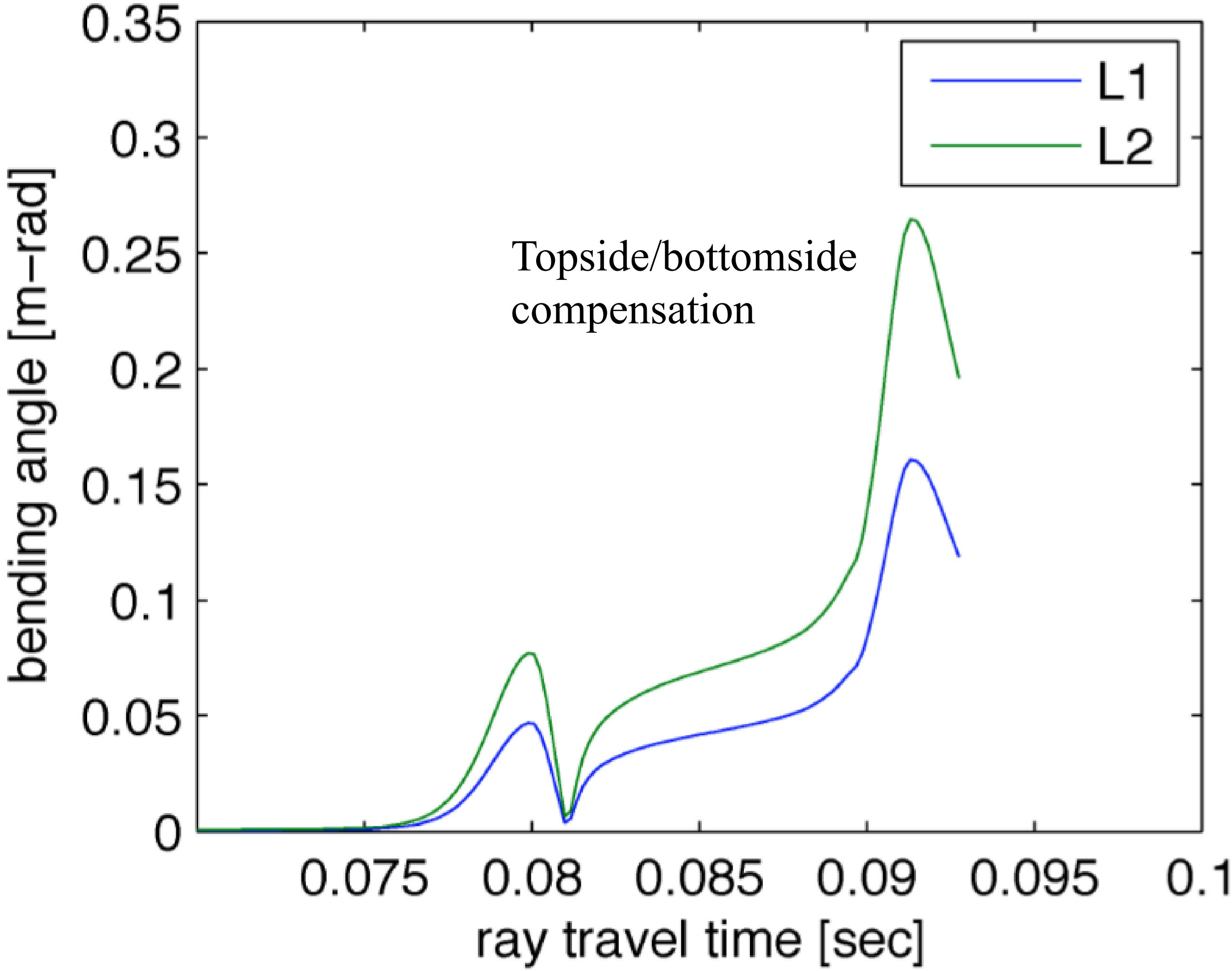


IRI
Oct 30, 2003



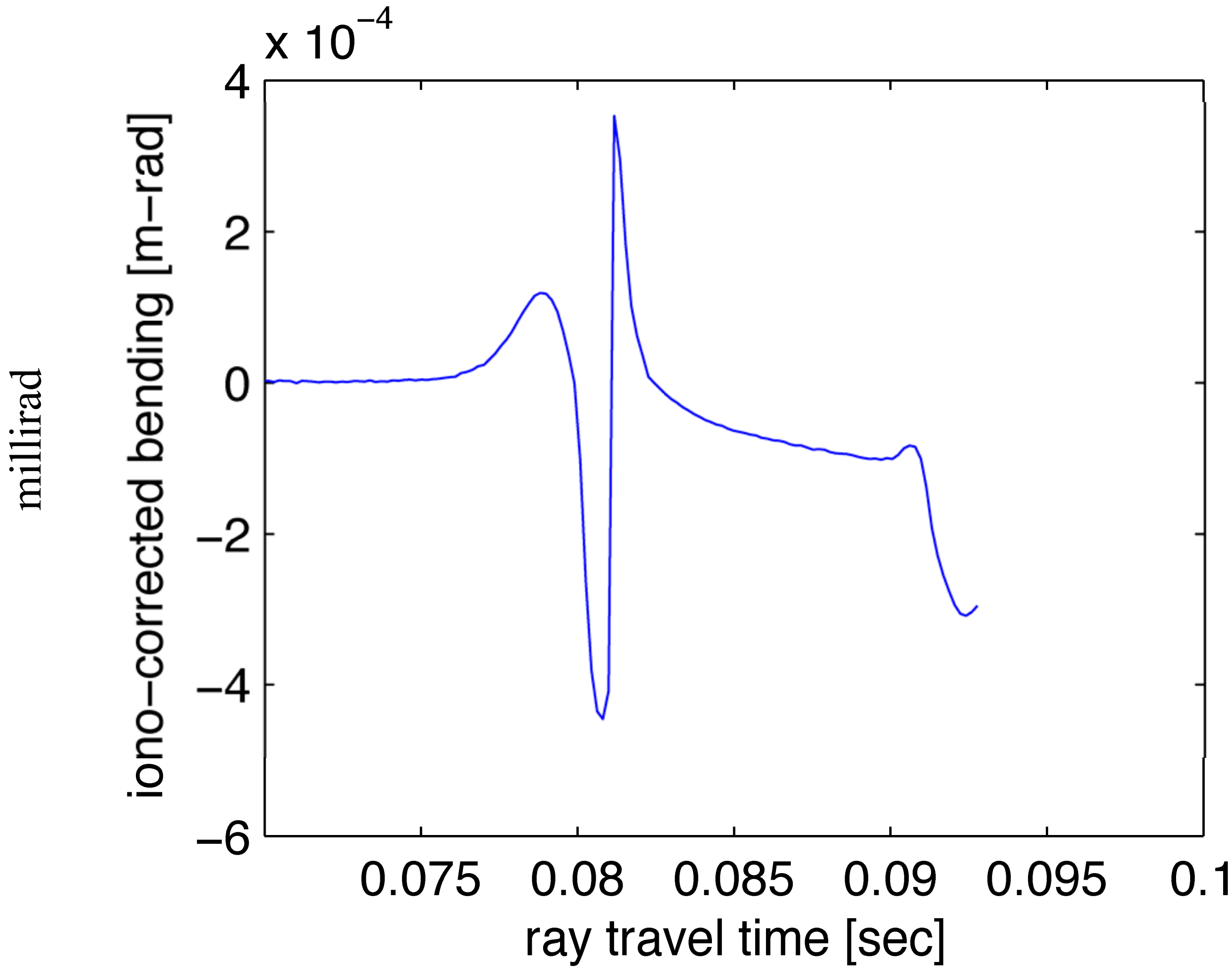
400 km
altitude
(CHAMP)

Bending Angle

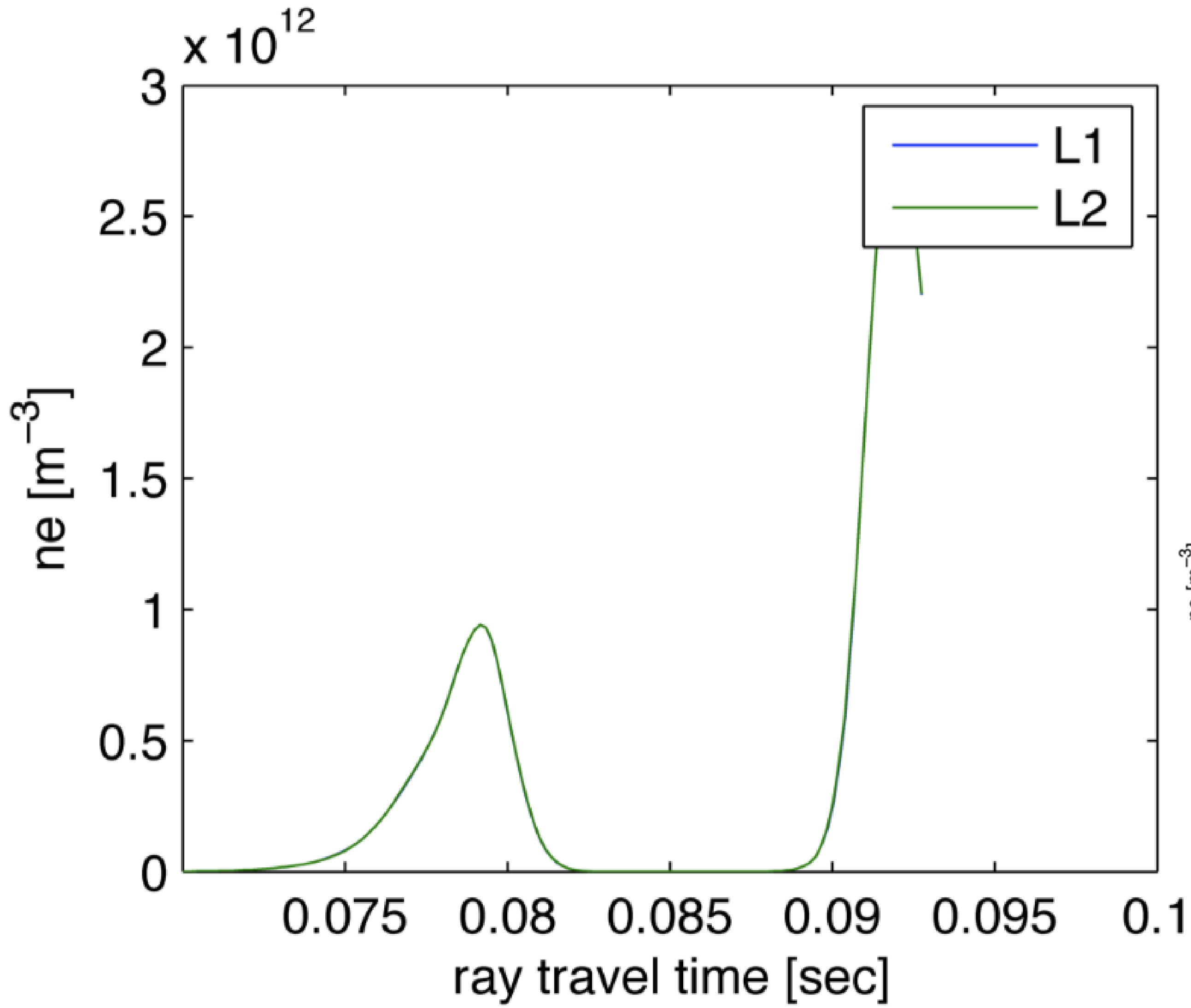


IRI
Oct 30, 2003

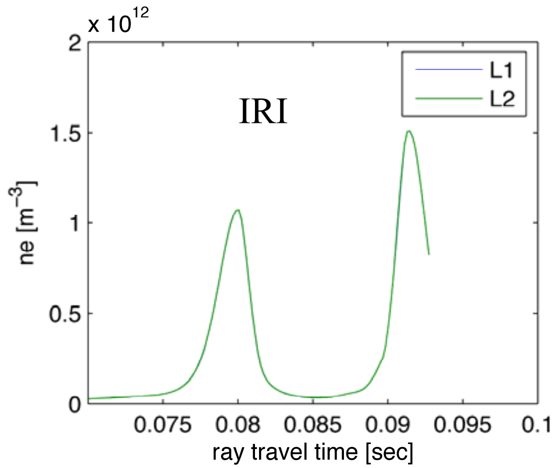
Residual Bending Angle



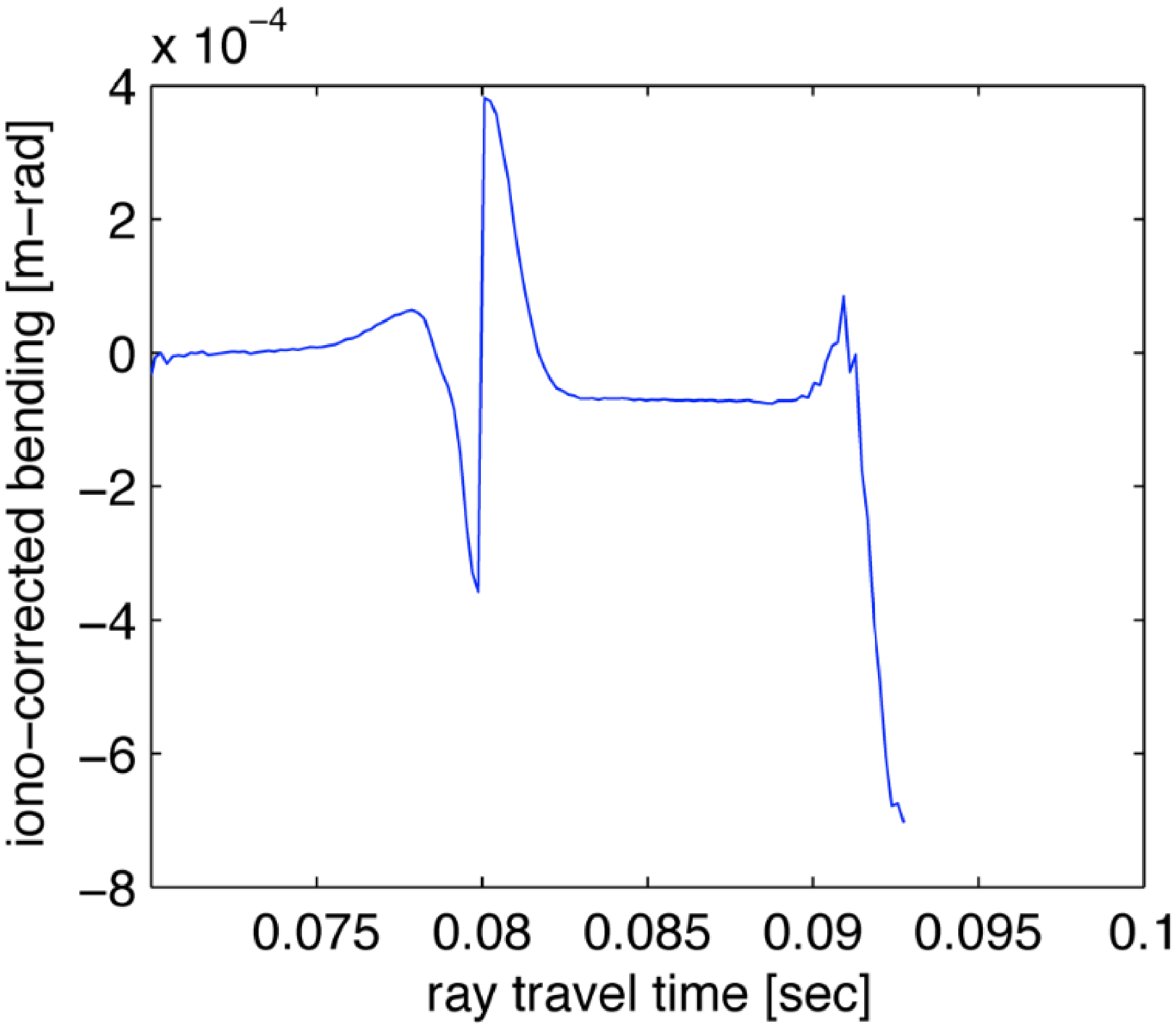
GAIM: Oct 30, 2003 "Superstorm"



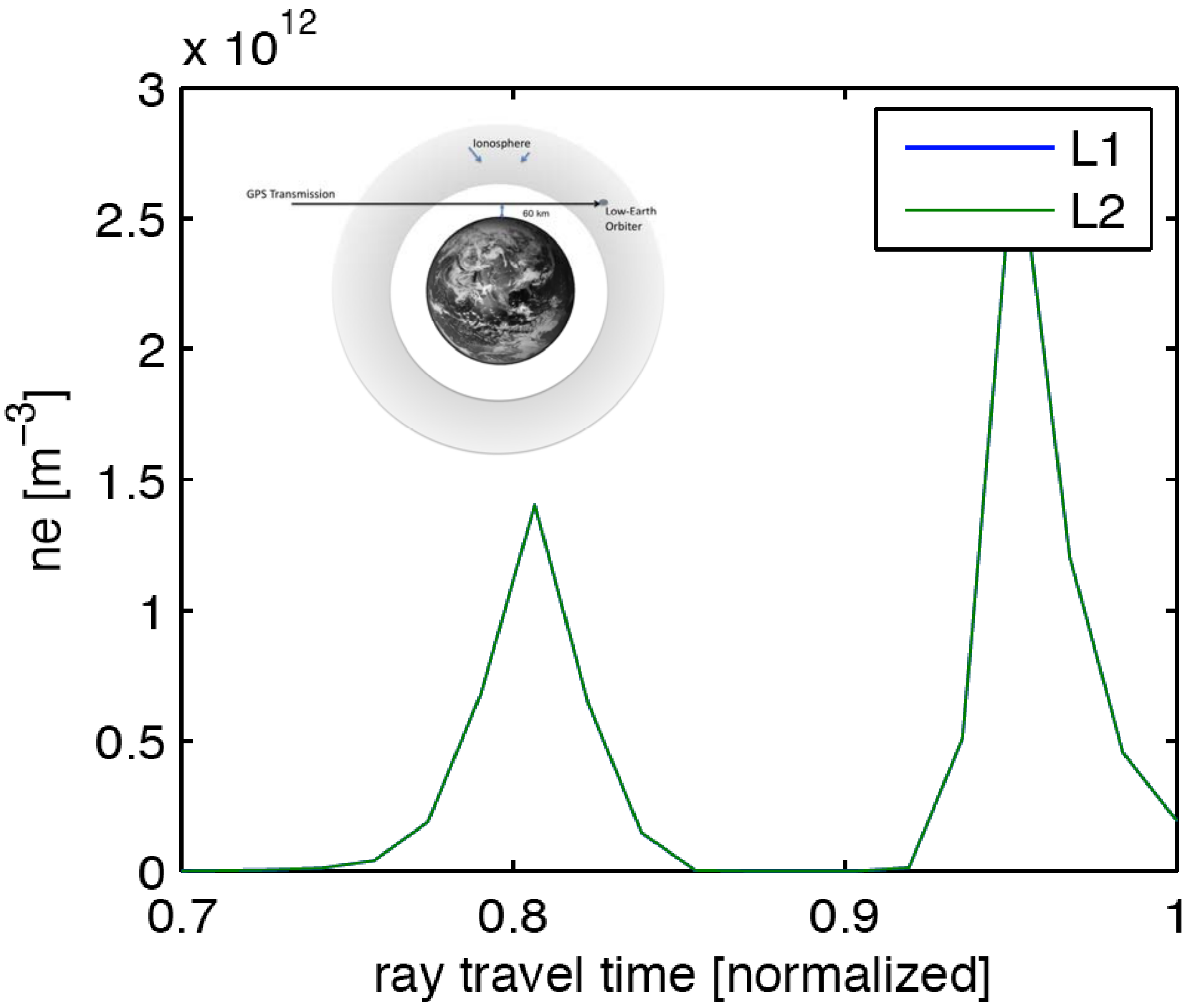
- CHAMP
- Northern hemisphere daytime
- Larger horizontal gradient



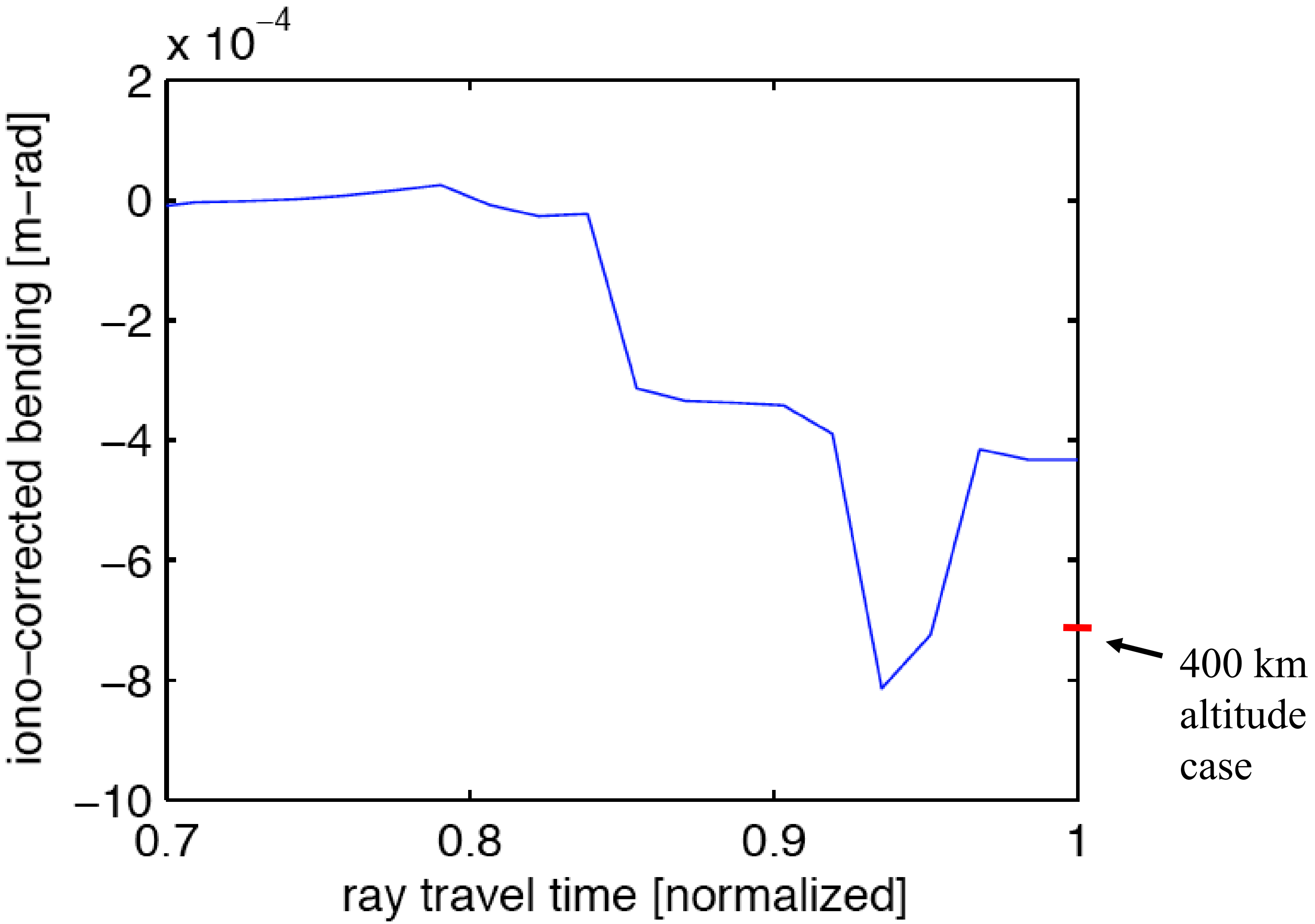
Residual Bending Angle "Superstorm"



LEO Altitude Of 730 km



Residual Bending Angle – 730 km LEO



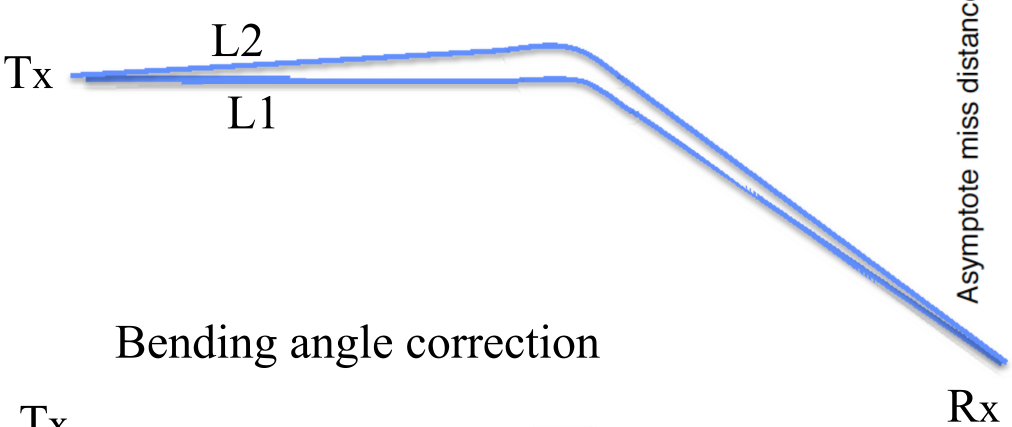
Characterization Summary

- **Extending past results suggests need for additional mitigation**
- **Major factors affecting ionospheric residual are spherical asymmetry and orbit altitude**

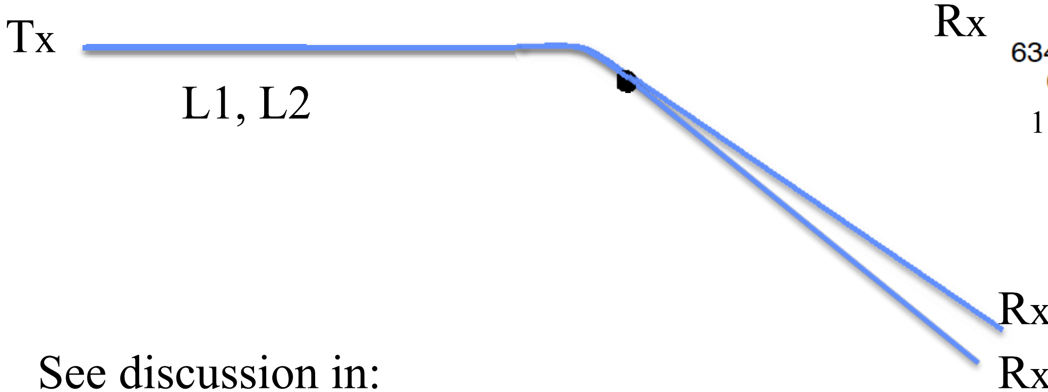
Mitigation

Bending Angle Correction

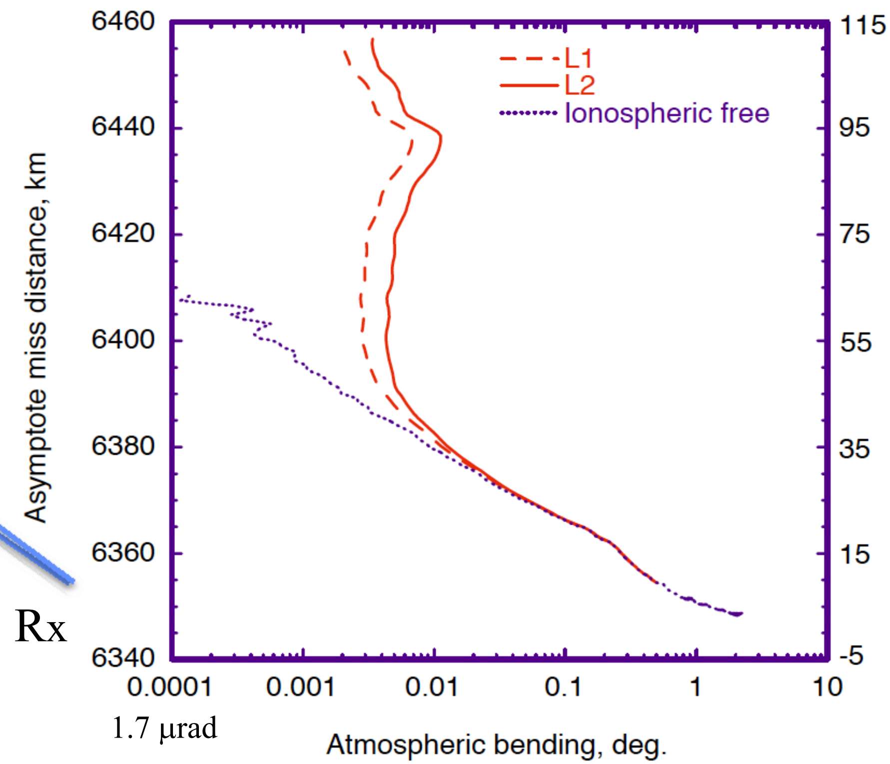
Phase delay correction



Bending angle correction



Partial correction for raypath separation



See discussion in:

Vorob'ev, V. V., and T. G. Krasil'nikova, Estimation of the accuracy of the atmospheric refractive index recovery from Doppler shift measurements at frequencies used in the NAVSTAR system, Phys. Atmos. Ocean, 29, 602-609, 1994.

Bending Angle Correction

- **Assumes linear relation between bending angle and refractive index**
  - **Refractive index ~1/*f*²**
- **Residual error due to non-linearity**

Eq. (1)
Bending angle correction

$$\alpha_c(a) = \left[\frac{f_1^2}{f_1^2 - f_2^2}\right]\alpha_1(a) - \left[\frac{f_2^2}{f_1^2 - f_2^2}\right]\alpha_2(a)$$

Eq. (2)
Residual error in bending

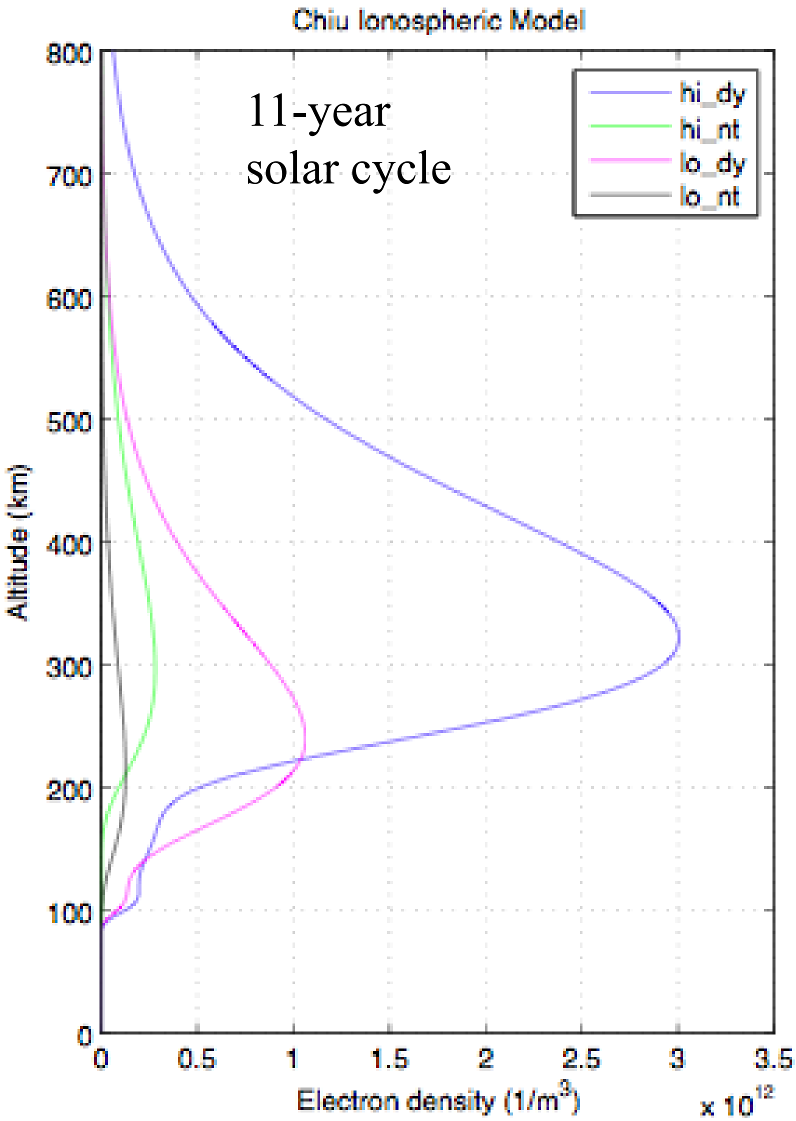
$$\Delta\alpha(a) = \frac{C^2}{f_1^2 f_2^2} a \frac{d^2}{da^2} \int_a^\infty \frac{x N_e^2 dx}{\sqrt{x^2 - a^2}}$$

Eq. (3)
Residual error in refractivity

$$\Delta N = \frac{10^6}{\pi} \int_a^\infty \frac{\Delta\alpha(x) dx}{\sqrt{x^2 - a^2}}$$

See Syndergaard, Radio Science, 2000

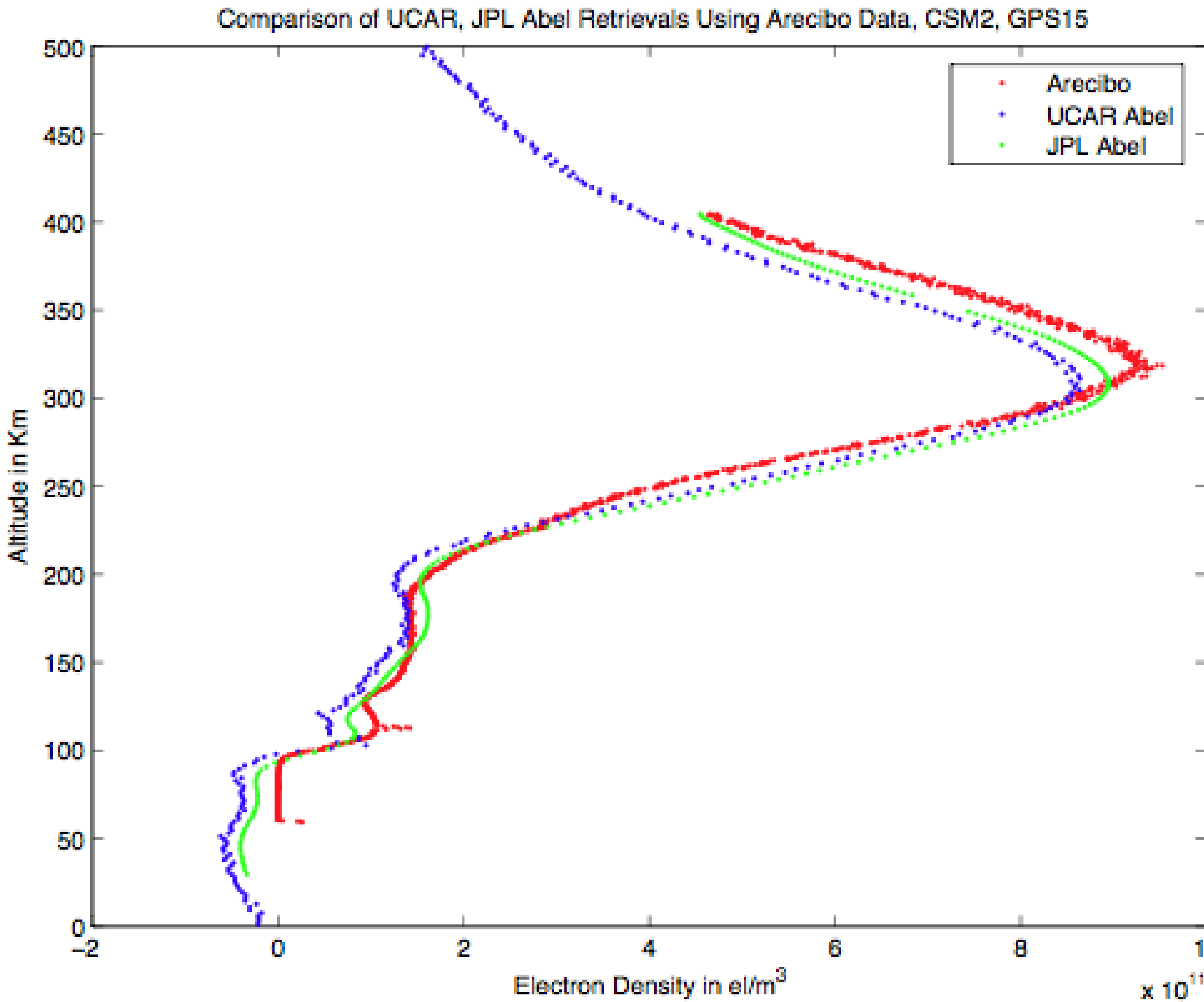
Calculation Of Residual BA Error



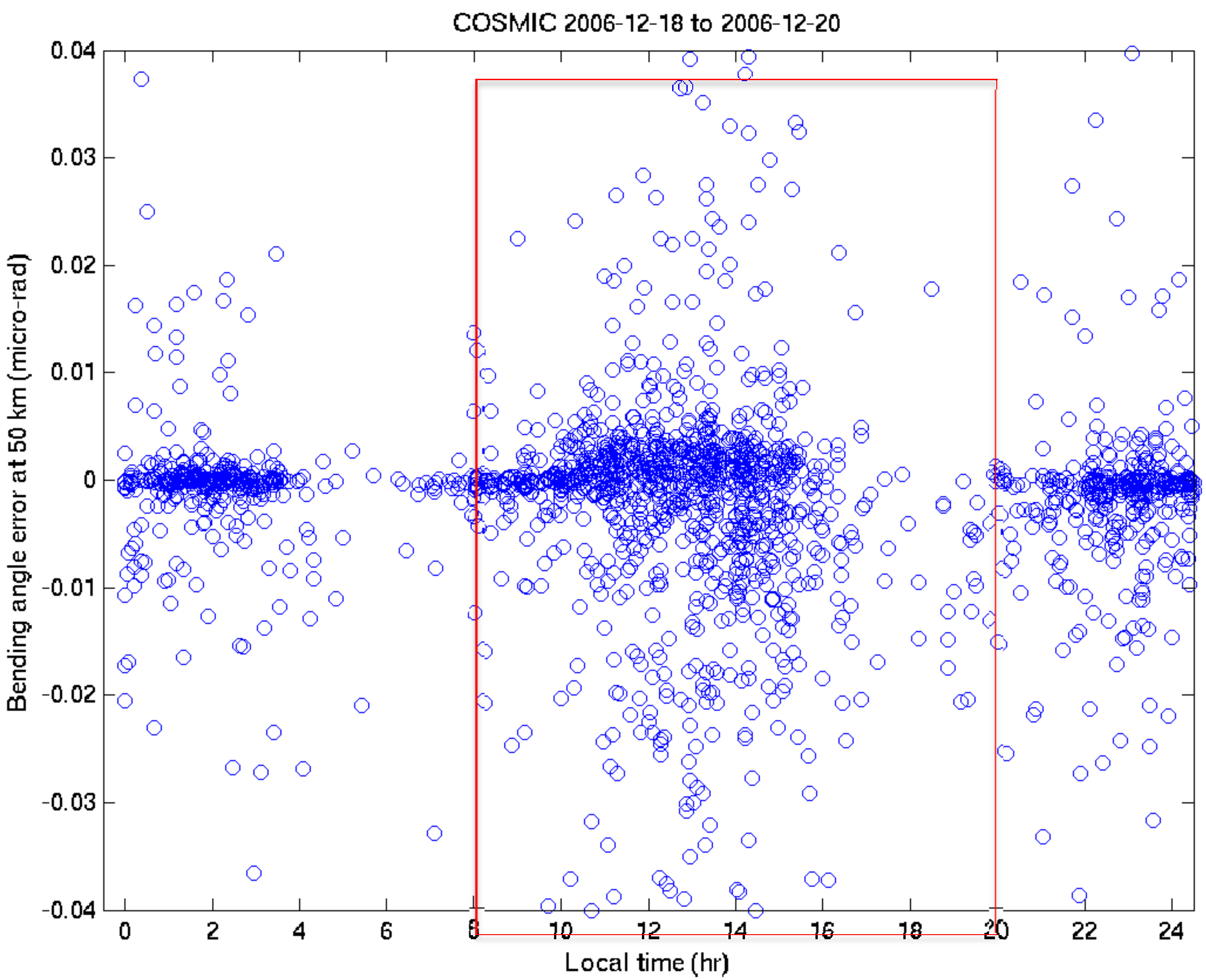
Residual bending angle error at 50 km in micro-rad (based on typical conditions from the Chiu ionospheric model), from Eq. (2)

	solar max	solar min
daytime	0.15	0.043
nighttime	0.0016	0.0008

Electron Density Profile Retrievals



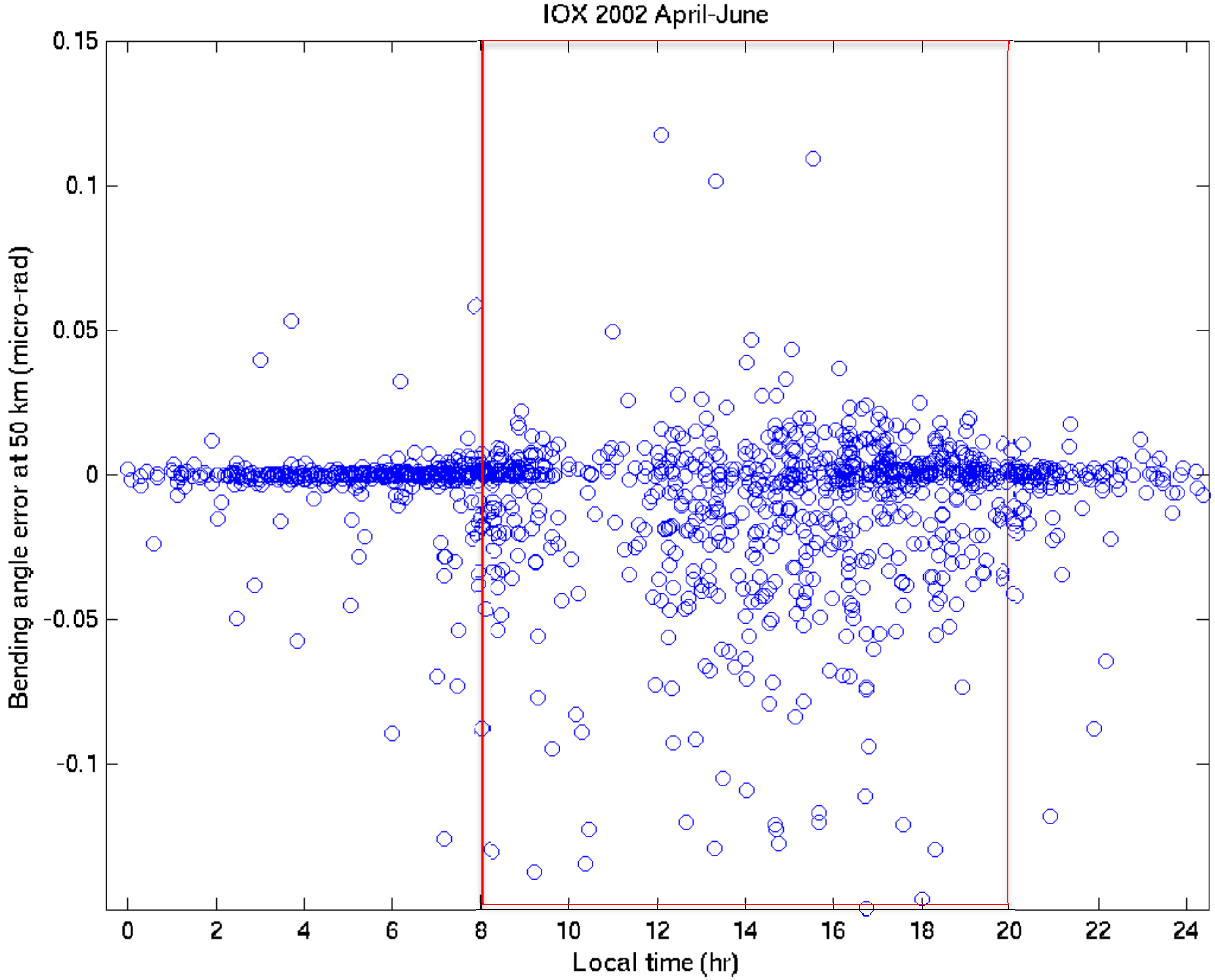
Bending angle residual error from cosmic iono occultation data



Notes:

(1) Increased error during daytime
(2) Daytime errors are small relative to the Chiu model solar min. Why?

Bending angle residual error from IOX iono occultation data



Notes:

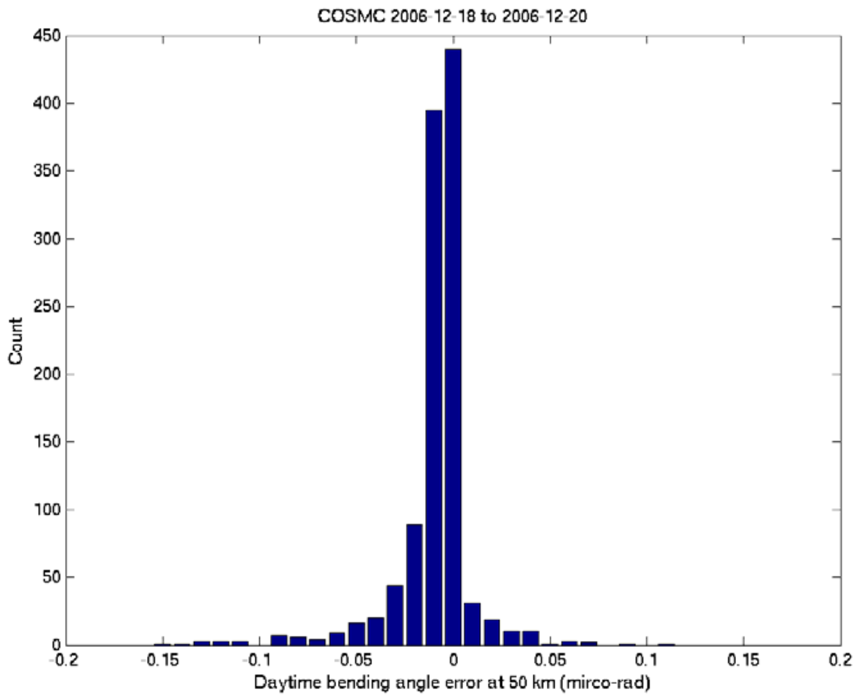
(1) Daytime errors have larger scatters compared to cosmic in 2006, but…

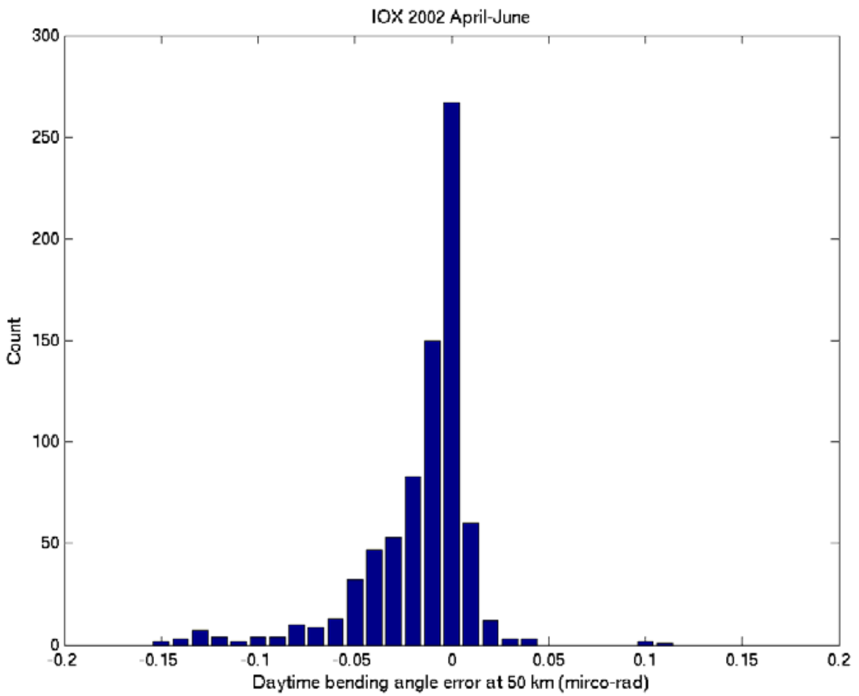
(2) Large number of occultations have very small residual errors.

Bending angle residual error distribution

COSMIC

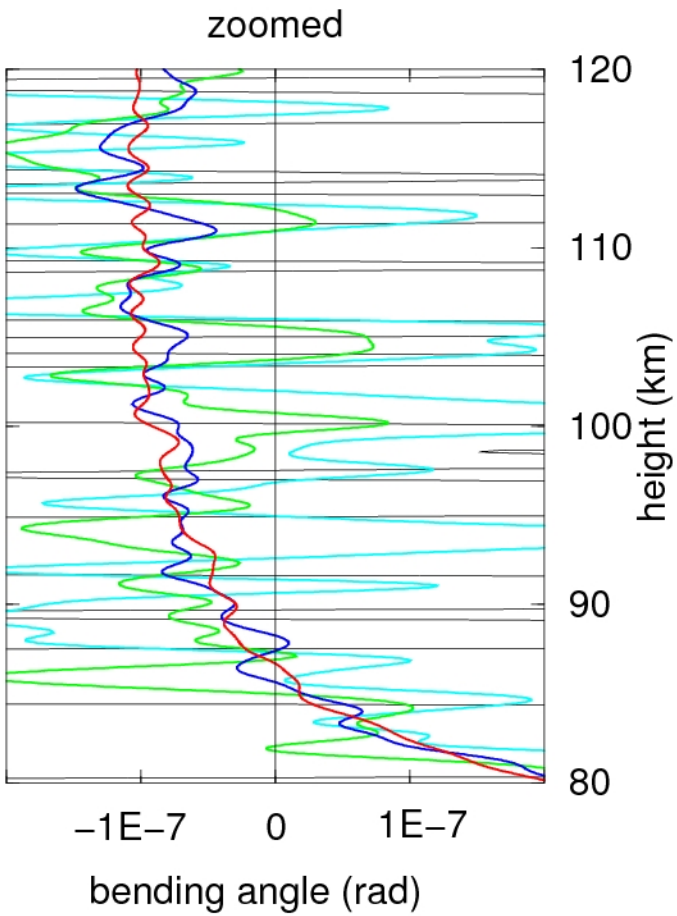
IOX





UCAR: COSMIC Residual Bending

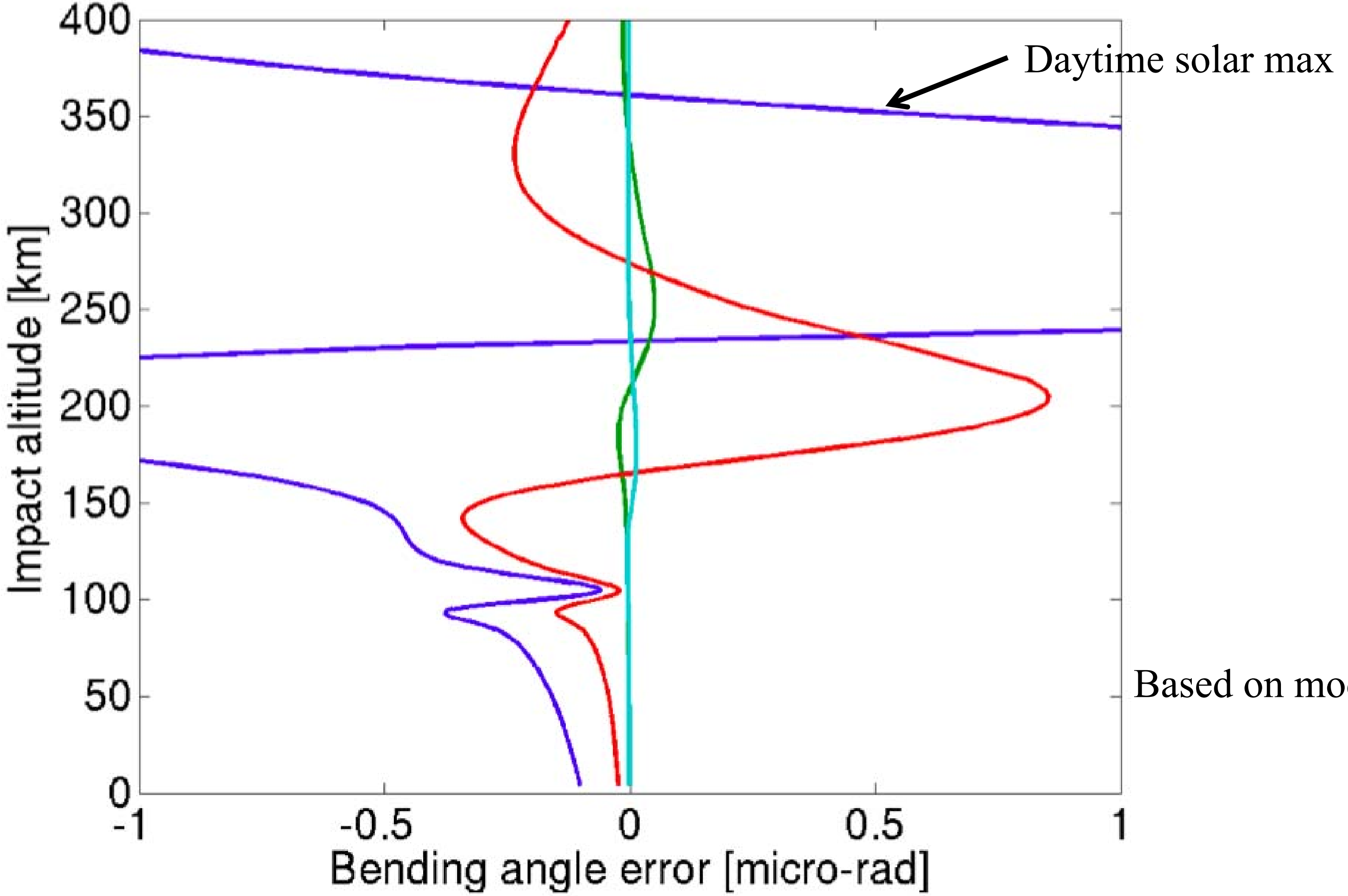
individual occultation; 100 occultations; 1000 occultations; 10000 occultations; 100000 occultations



Approaches 0.1 μrad, larger than our estimates based on equation (2)

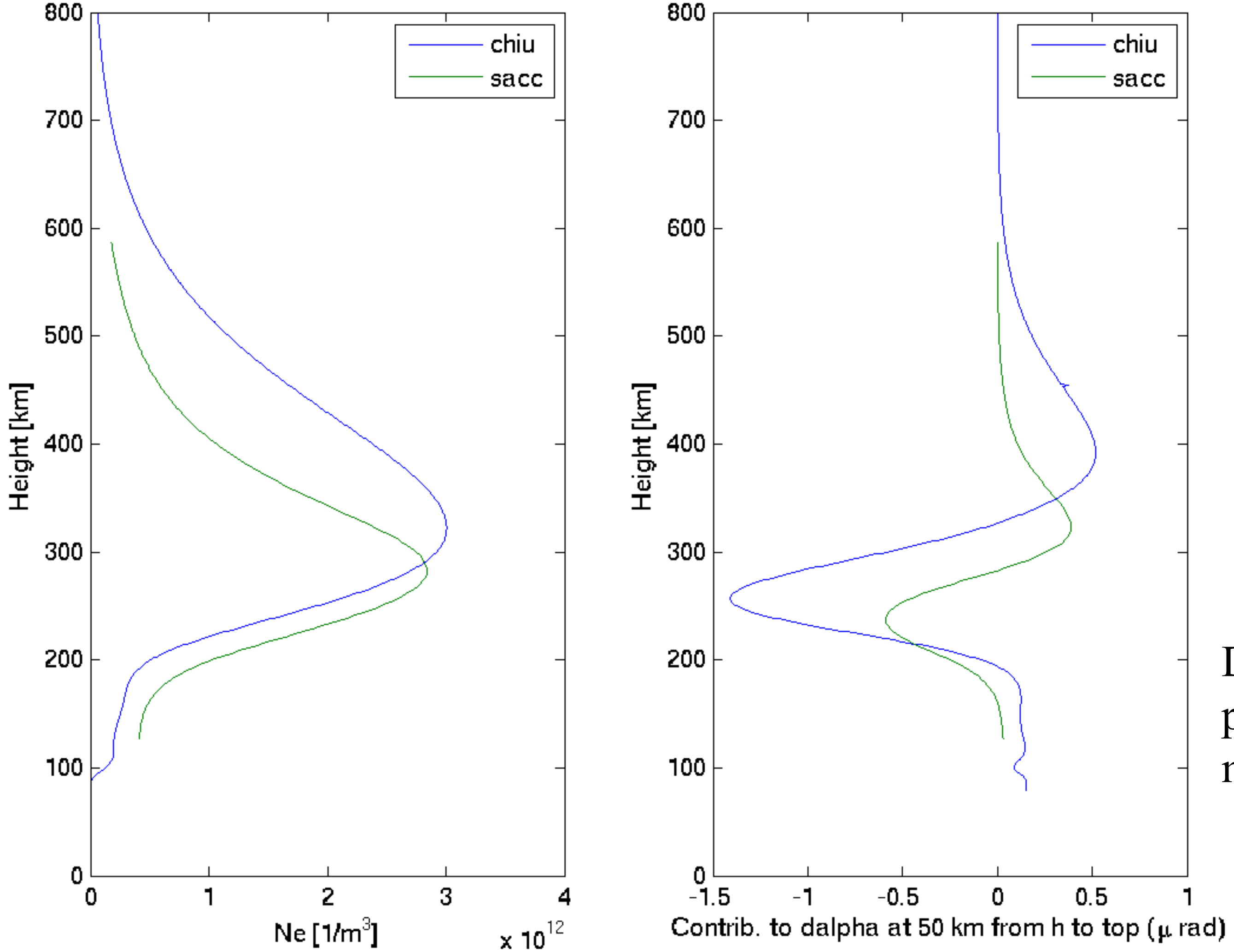
C. Rocken et al., CLARREO Requirements Workshop, 2010

Computed Residual Error Versus Altitude



Based on model

CHIU Model vs SAC-C



Details of the profile shape matter

Analysis

- **Correction term appears too small assuming retrieved electron density estimates, compared to ray-trace estimates**
- **Hypothesis: spherical symmetry assumption, upon which correction model is based, is insufficient (ionosphere is not so symmetric)**
  - **Note sensitivity of correction term to detailed structure, as revealed in altitude dependence**
- **Models produce more realistic correction term estimates compared to retrieved electron density profiles**

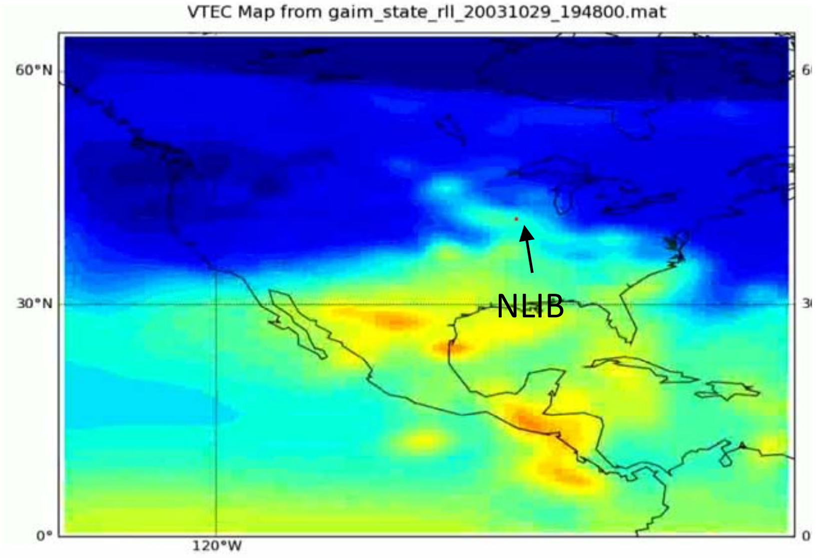
Tools

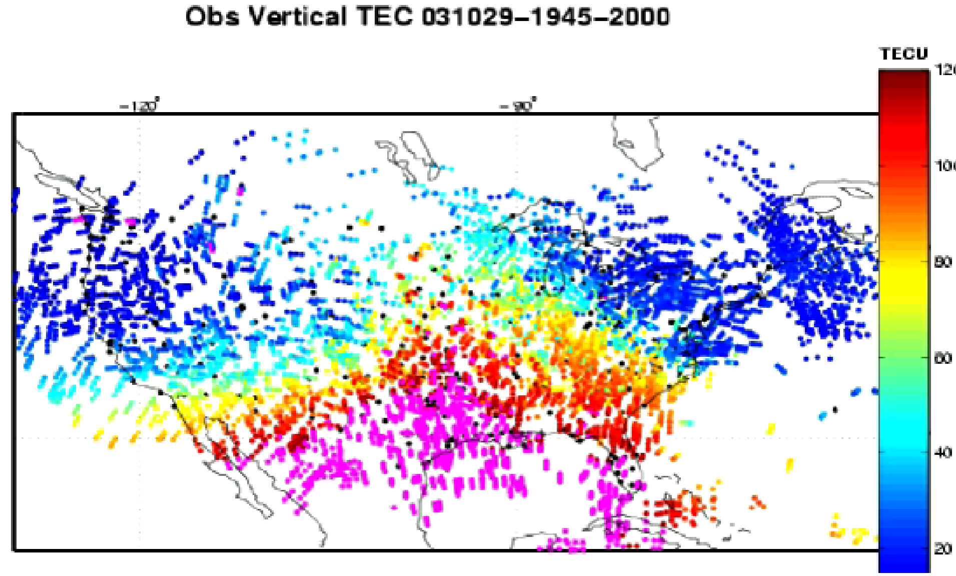
Eq. (1)
Bending angle correction

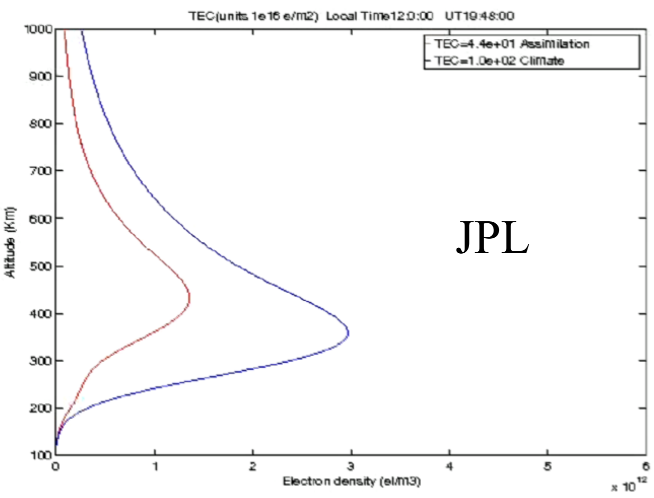
$$\alpha_c(a) = \left[\frac{f_1^2}{f_1^2 - f_2^2}\right]\alpha_1(a) - \left[\frac{f_2^2}{f_1^2 - f_2^2}\right]\alpha_2(a)$$

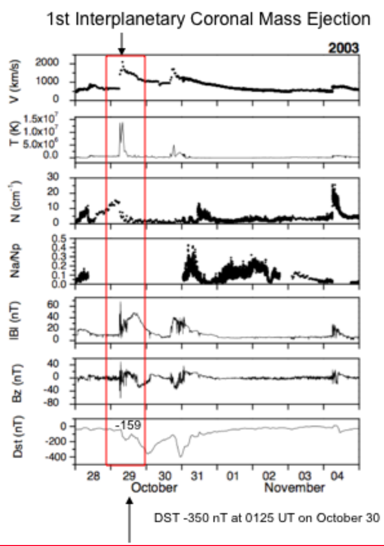
- **Estimate bending due to ionosphere using an assumed electron density profile**
  - **Gorbunov et al., 1996 – spherical symmetry assumed**
- **Use the Global Assimilative Ionosphere Model to compute bending angle correction**
- **Use Global Ionospheric Maps (TEC) to infer horizontal gradients**

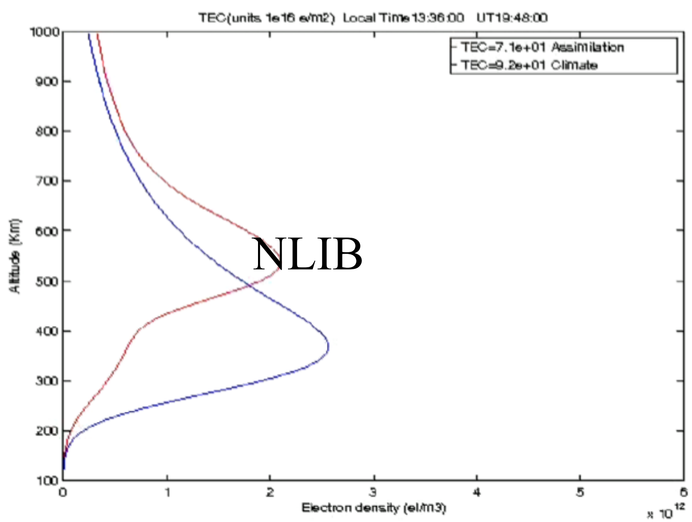
Storm Day: Oct 29, 2003, NGAIM And Truth Storm Features at NLIB



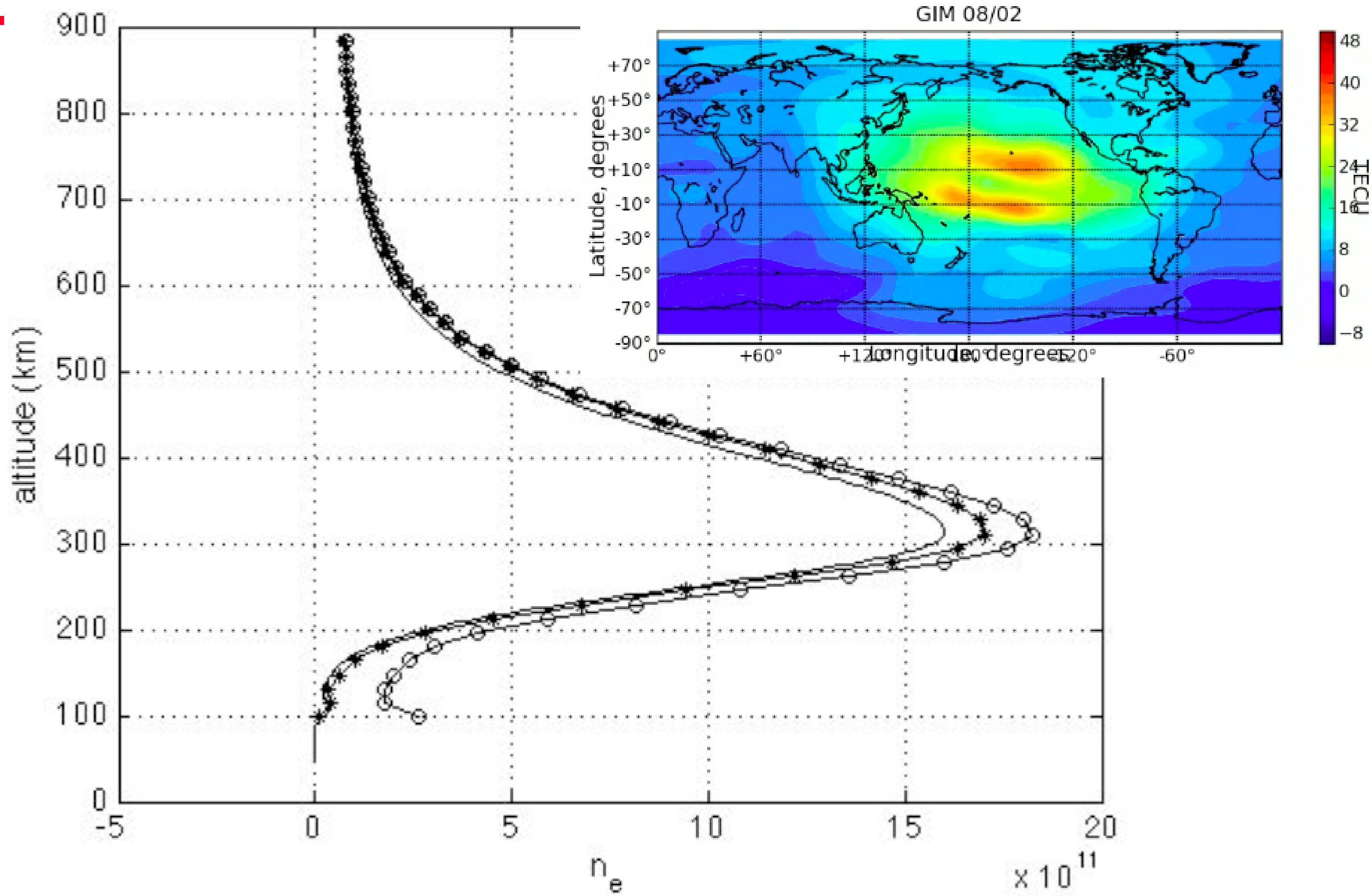








"Improved Abel" Retrieval



Kulikov et al., "Electron Density Retrieval from Occulting GNSS Signals Using a Gradient-Aided Inversion Technique," Adv. Spc. Res., *in press*

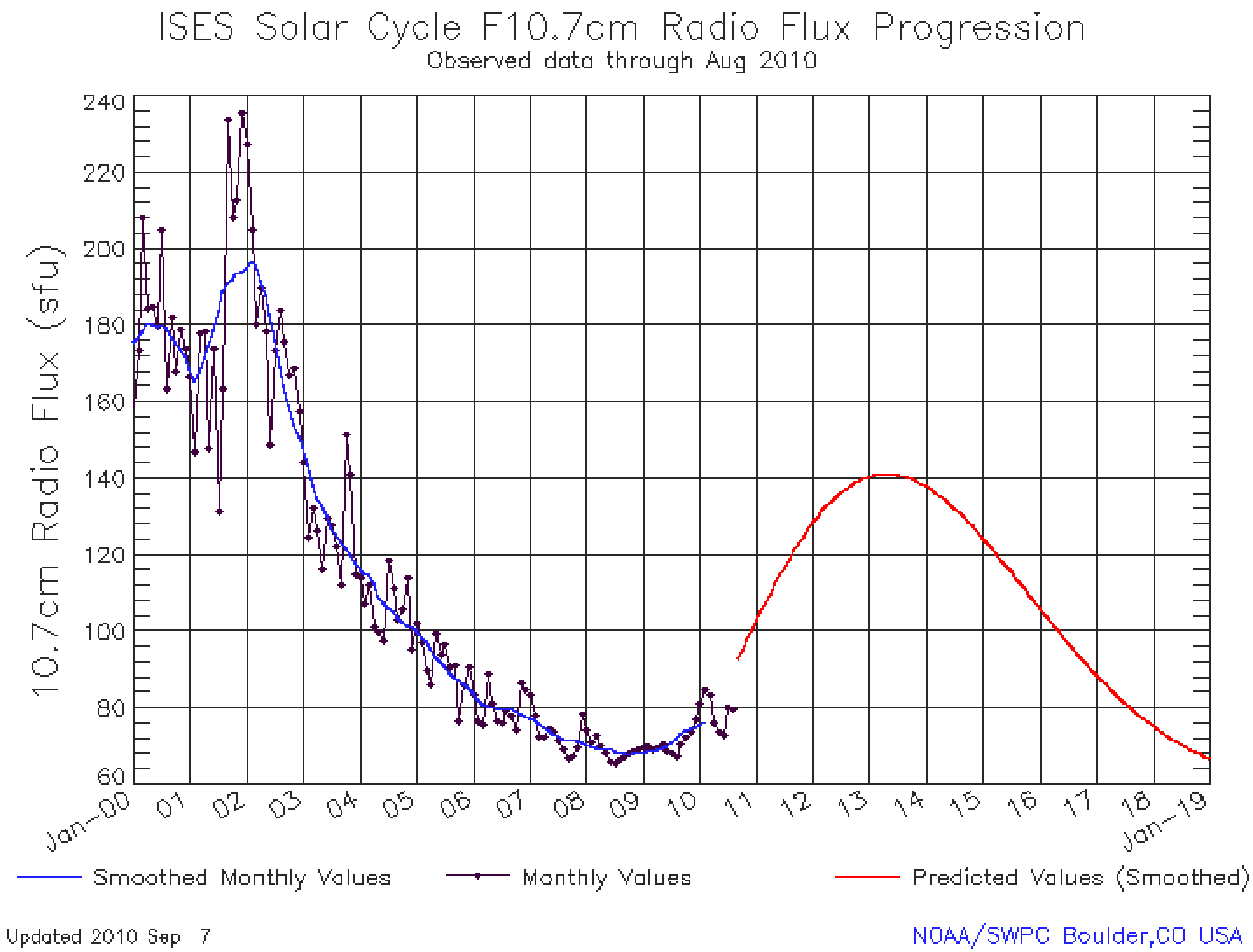
See "CEDAR Workshop" presentations 2010

Summary

- Past work suggests need to apply additional correction approaches to meet stringent climate requirements
  - Gorbunov et al., Syndergaard, Kursinski et al., Rocken et al.
- Spherical symmetry in the ionosphere may be a limiting assumption in mitigation
- Solutions would then consist of estimated 3D electron density distributions
  - GAIM
  - Assisted Abel (global ionospheric TEC maps + RO)
- Impact of LEO altitude and climate studies
  - Note that bending angle correction may be a common mode error for a given “constellation”

Future Work

- **Assess impact of spherical asymmetry in additional cases**
  - **Other sources of error also? Syndergaard et al., 2000 did not see a large effect from asymmetry**
- **Recommendation: implement different approaches at the different centers**
  - **Let's understand structural uncertainties due to large scale ionosphere error**
- **Assess statistical impact of small-scale errors**
  - **Mean zero or not?**


ISES Solar Cycle F10.7cm Radio Flux Progression
Observed data through Aug 2010
10.7cm Radio Flux (sfu)
240
220
200
180
160
140
120
100
80
60
Jan-00
01
02
03
04
05
06
07
08
09
10
11
12
13
14
15
16
17
18
Jan-19
Smoothed Monthly Values
Monthly Values
Predicted Values (Smoothed)
Updated 2010 Sep 7
NOAA/SWPC Boulder,CO USA