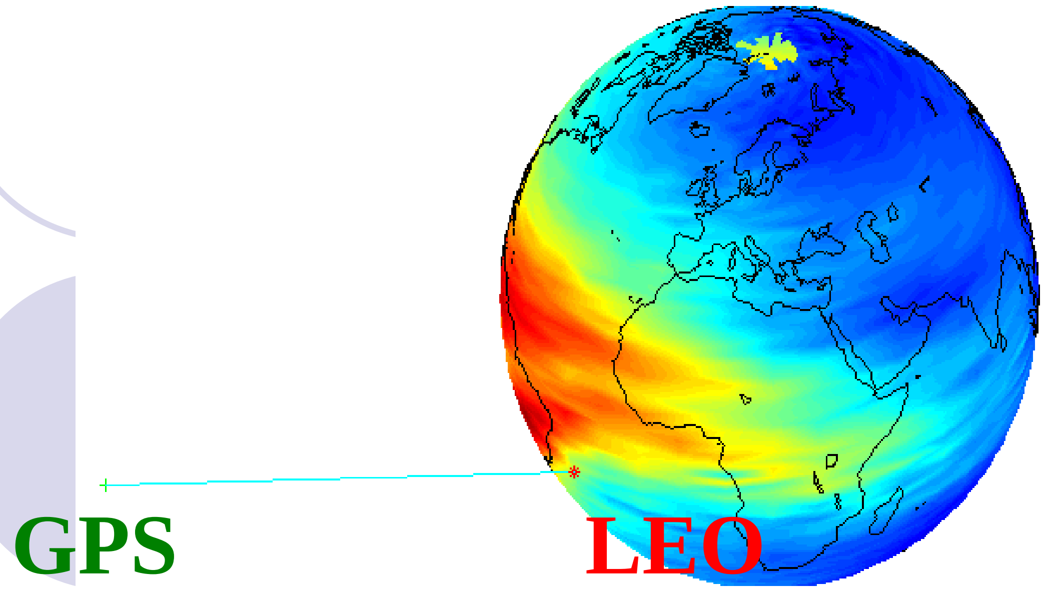
Radio occultation electron density retrieval aided by ground based GNSS observations



Xin'an Yue, Bill Schreiner , Ying-Hwa Kuo

COSMIC Program Office, UCAR

Content

- **Abel inversion and evaluation**

- **RO inversion aided by:**

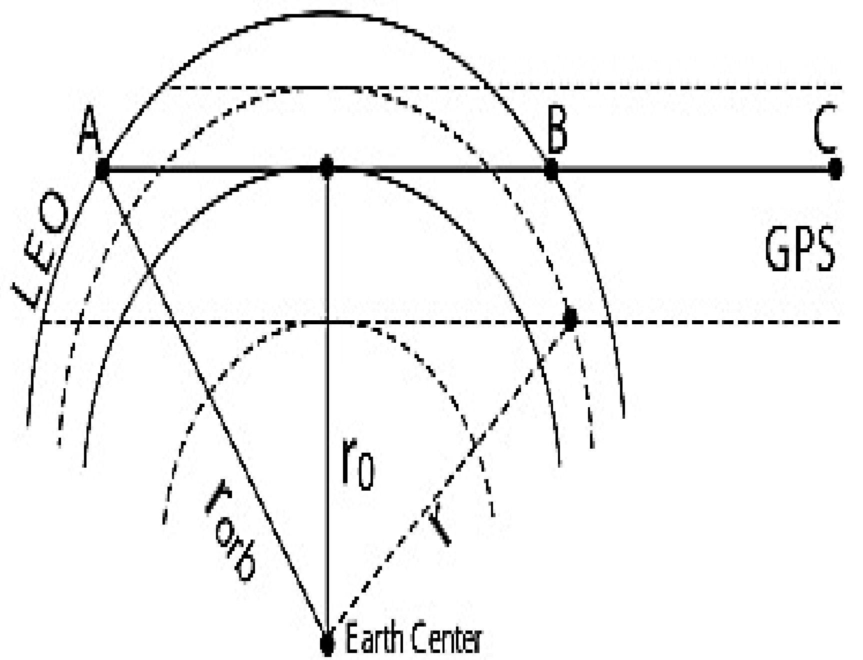
  1, GIM

  2, ground slant TEC

Abel inversion

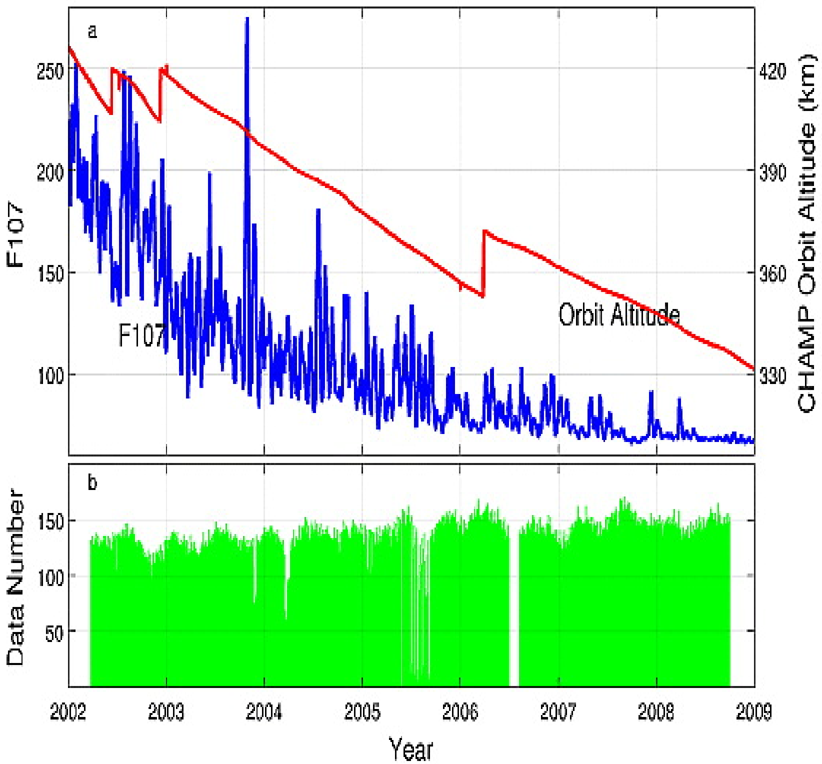
✓ **Assumptions used in Abel inversion (error source):**

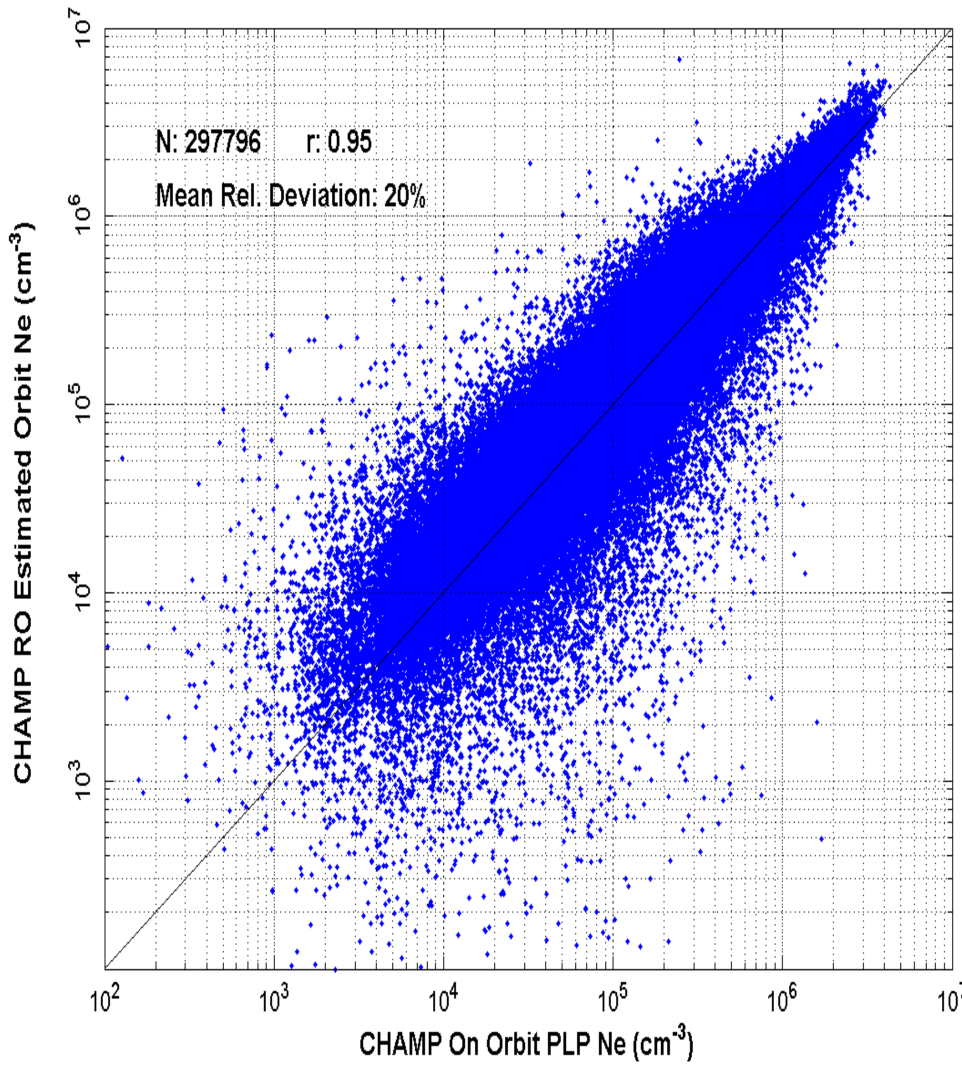
1. Straight-line signal propagation
2. Circular satellite orbit
3. occultation happens in the same plane
4. First-order estimation of electron density at the orbit altitude
5. Spherical symmetry of electron density



Orbit Ne estimation evaluation:

Comparing CHAMP RO estimated with PLP observed Ne on the orbit





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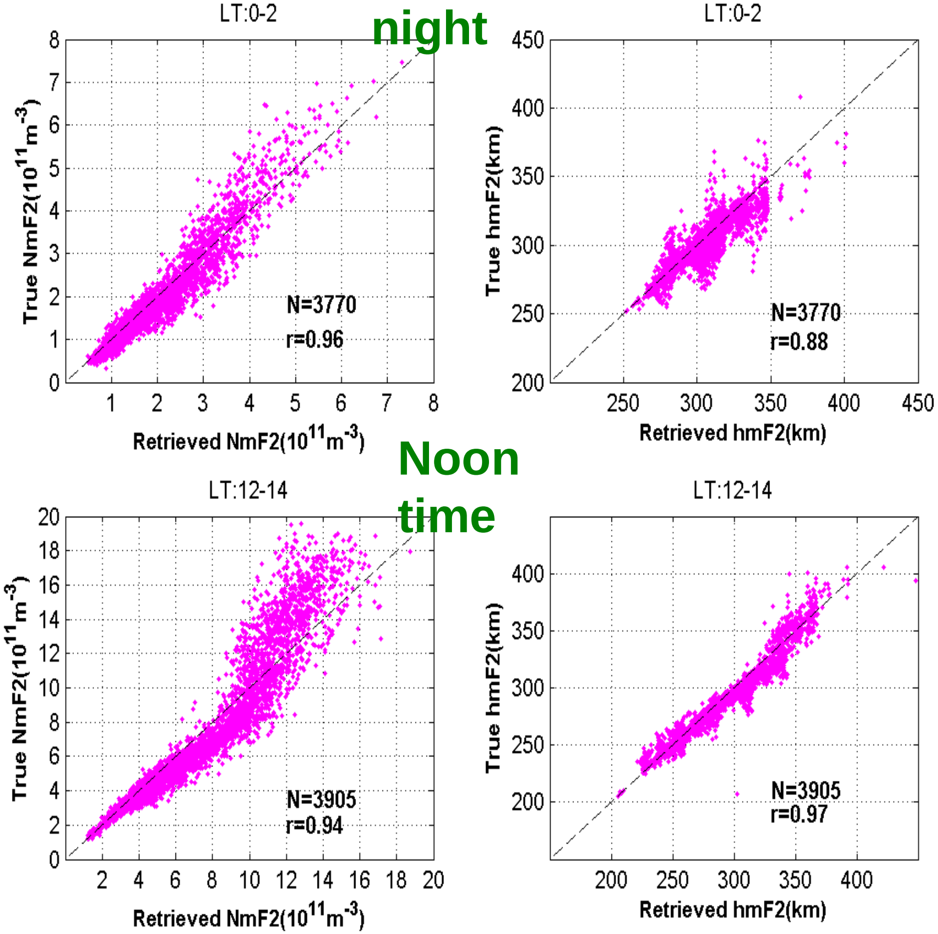
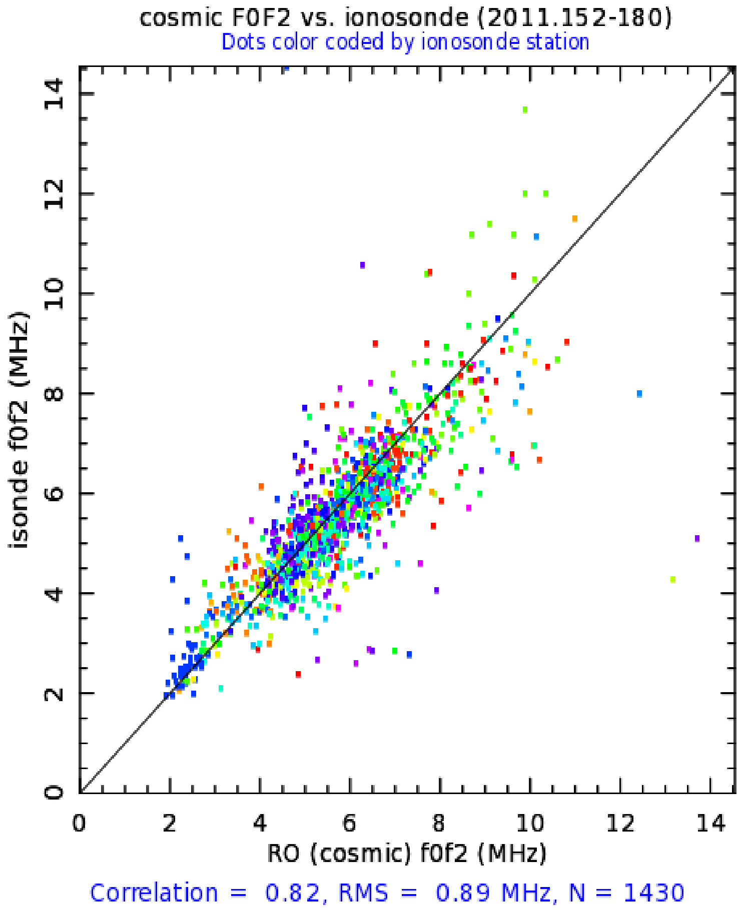
NmF2 & hmF2 : simulation and COSMIC validation

Middle night

Noon time





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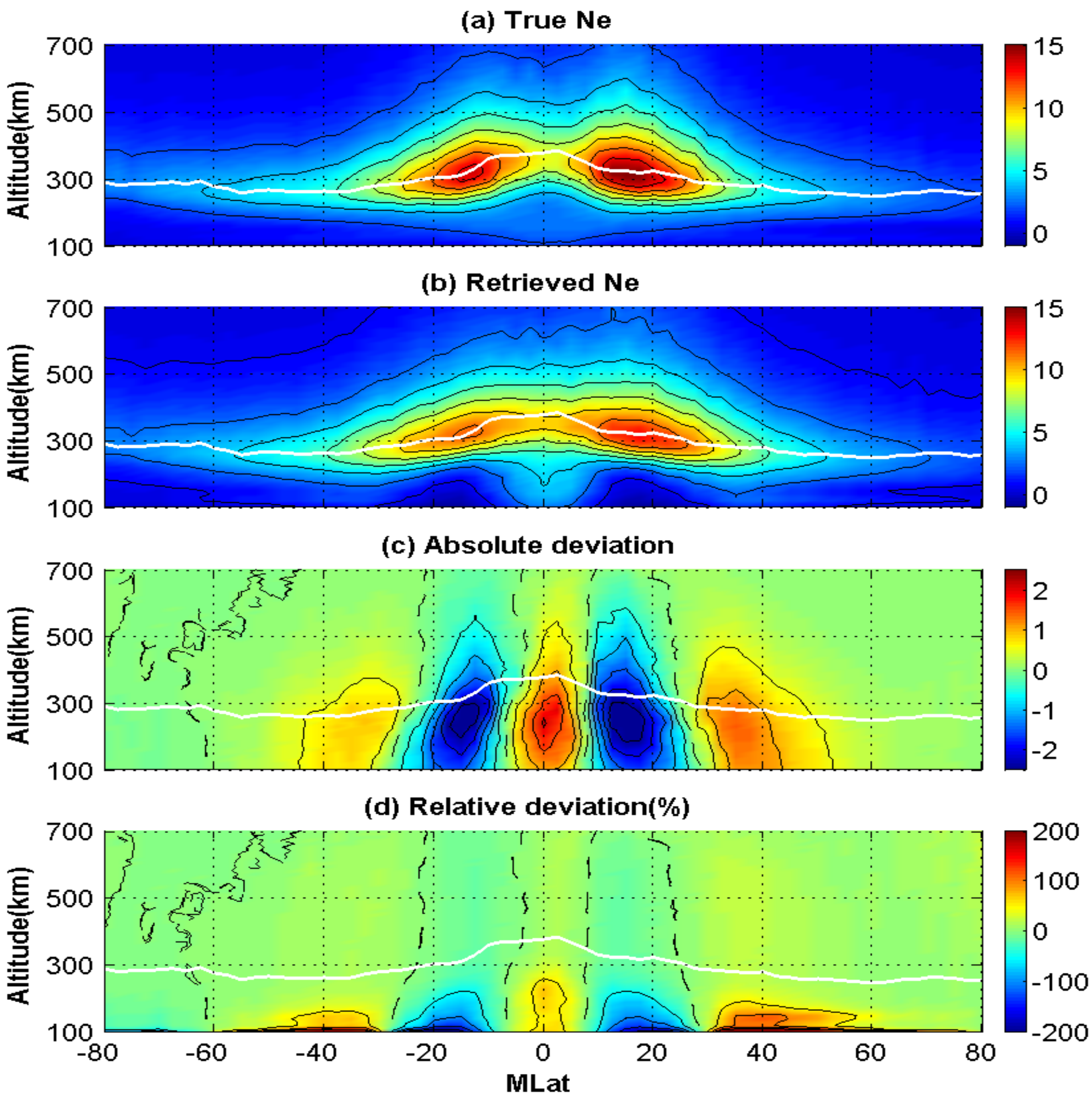
Abel Error distribution versus latitude and altitude: Modeling results, Spring Equinox

Noon time
LT=13

Unit:
$1\times10^{11}/m^3$



True' Ne

Retrieved Ne

Absolute Deviation

Relative Deviation

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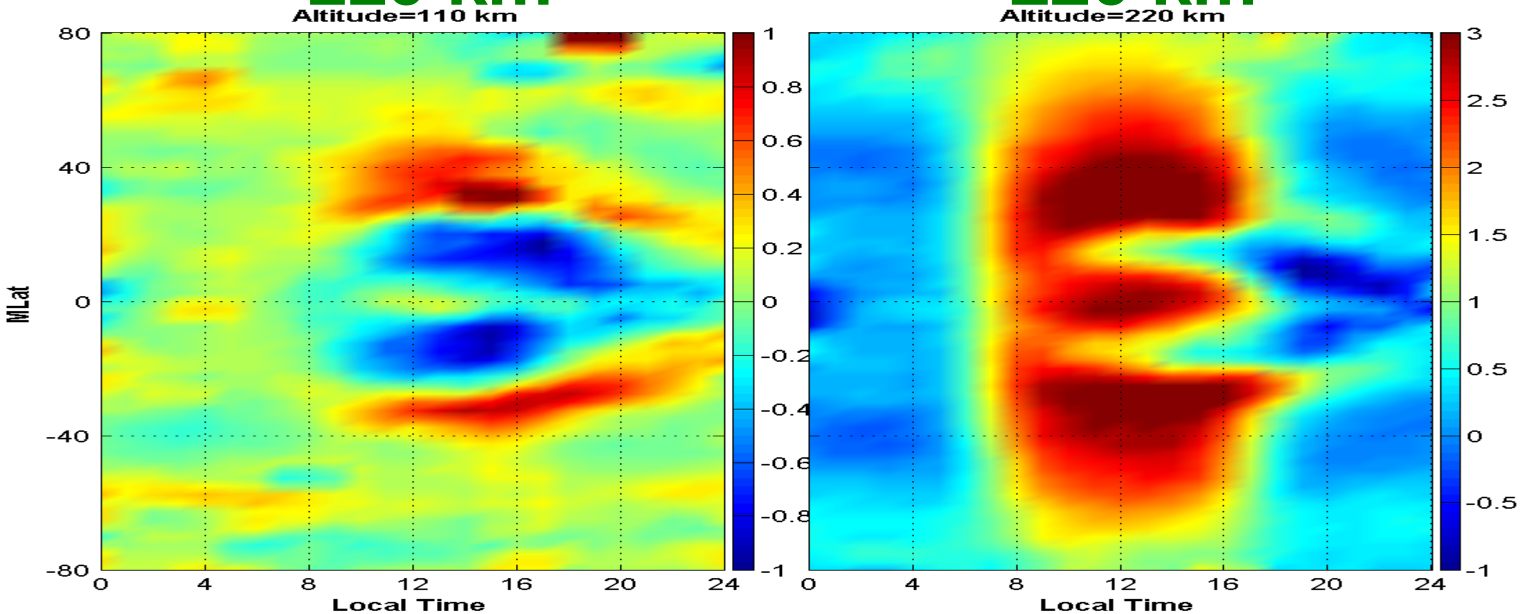
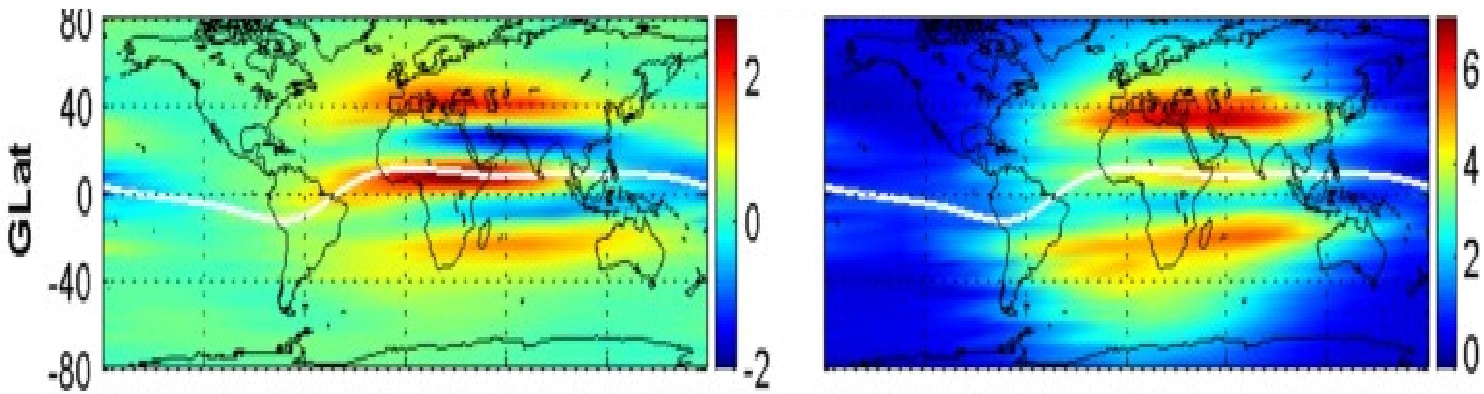
COSMIC observations (same time/duration as simulation):

110 km   220 km

COSMIC

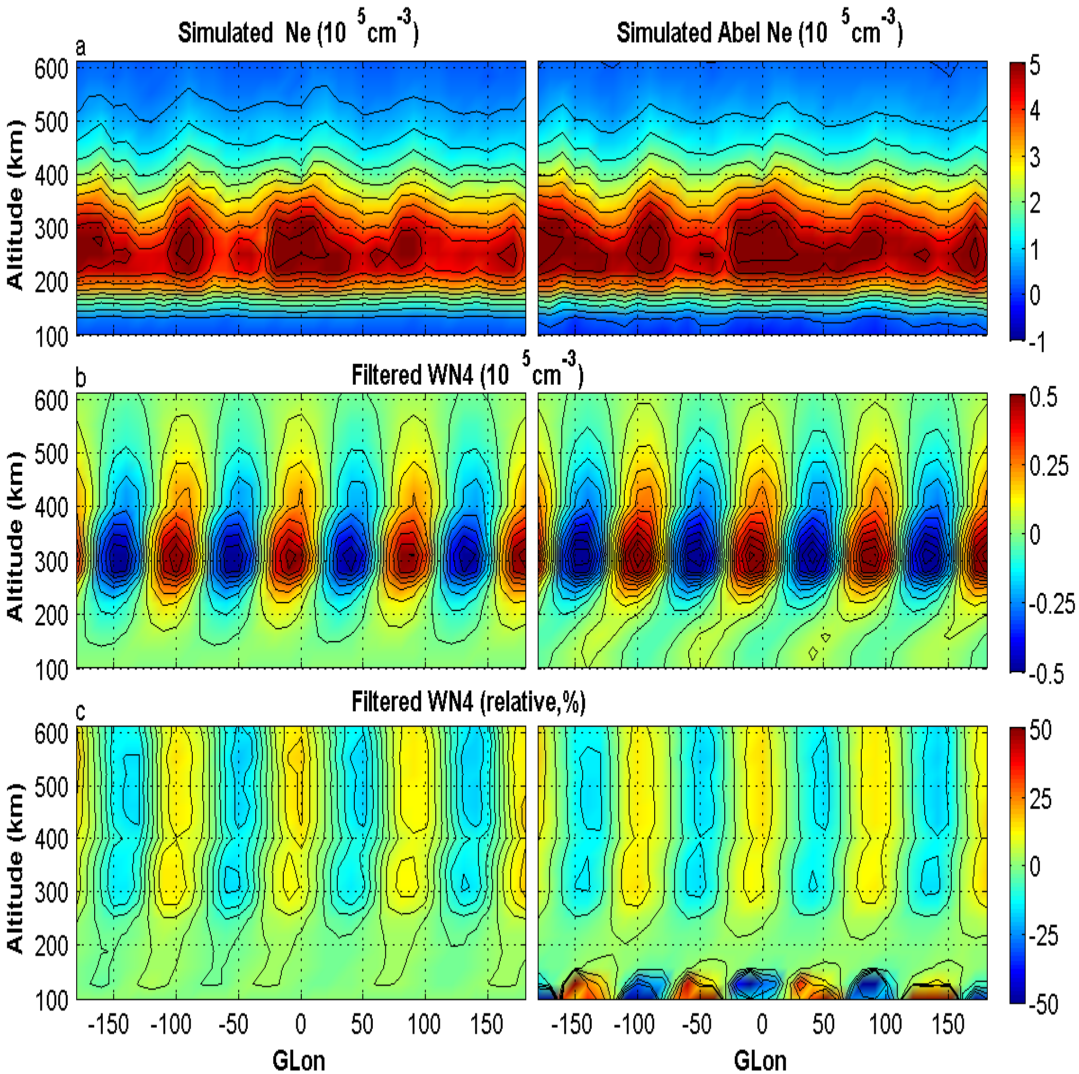


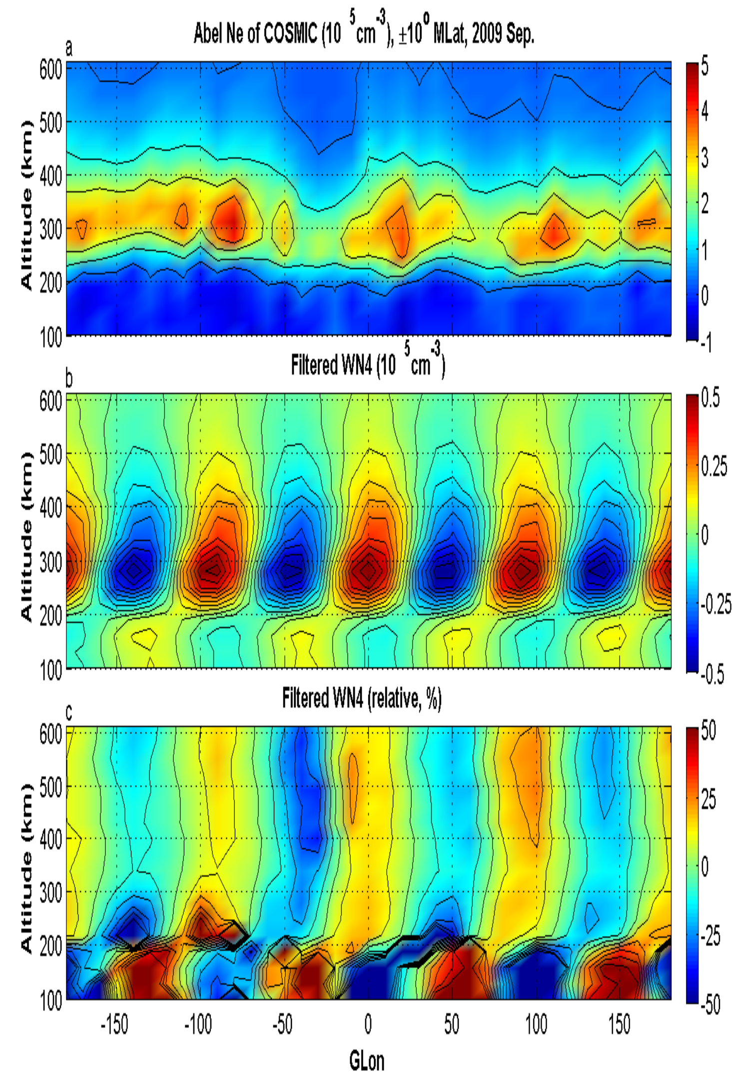
Abel retrieval from NeQuick model



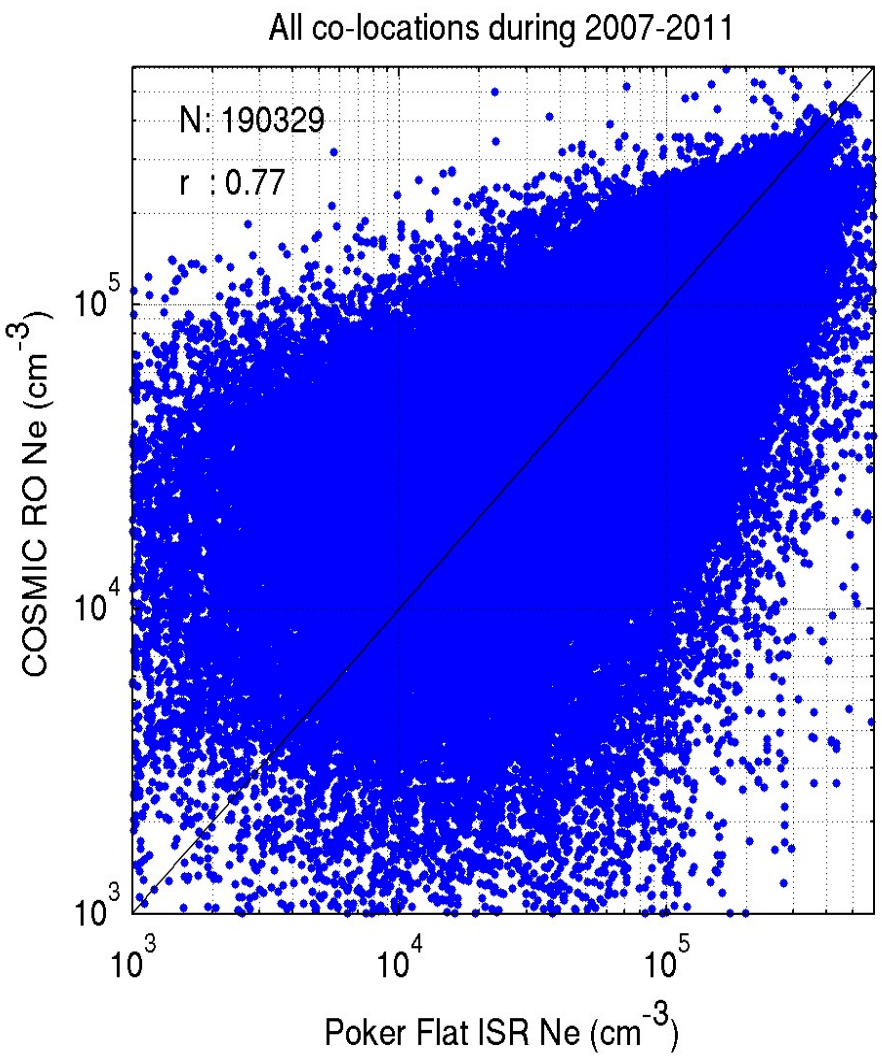
Unit: $1\times10^{11}/m^3$

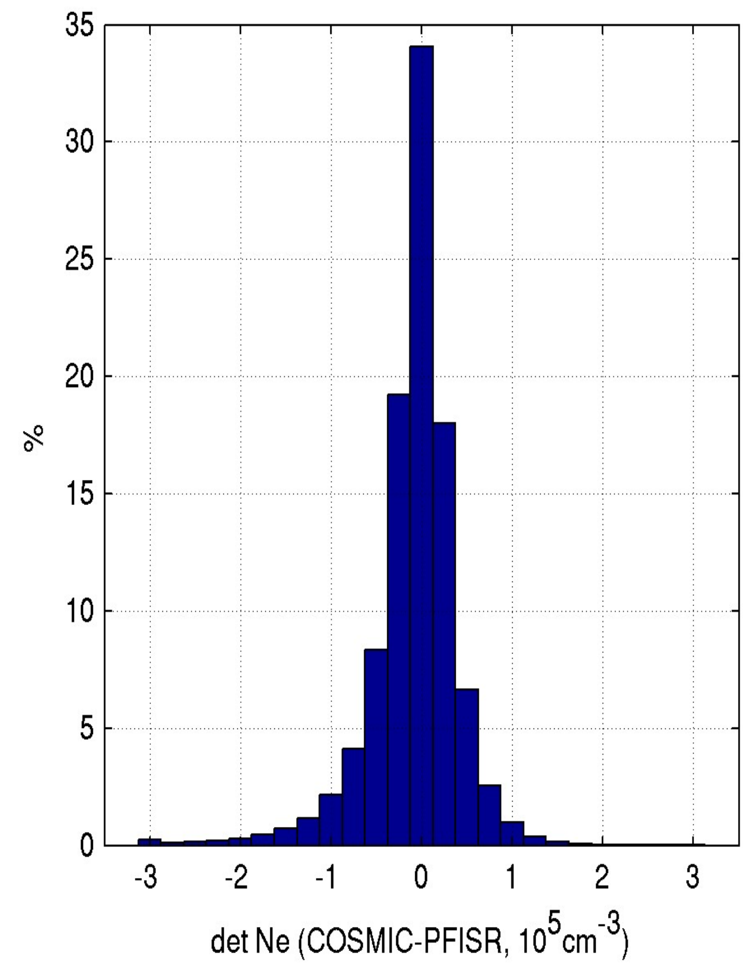
Artificial Wave Number 4 structure of Ne below F2 region made by the Abel inversion: Simulation & COSMIC 20-22 LT, Sep.





Comparison with Poker Flat Incoherent Scatter Radar (PFISR, 65N,147W) Ne, 2007-2011. (2.5 latitude, 5 degree in longitude, 15 minutes in local time, and 3 km in altitude)





✓ Abel inversion aided by GIM:

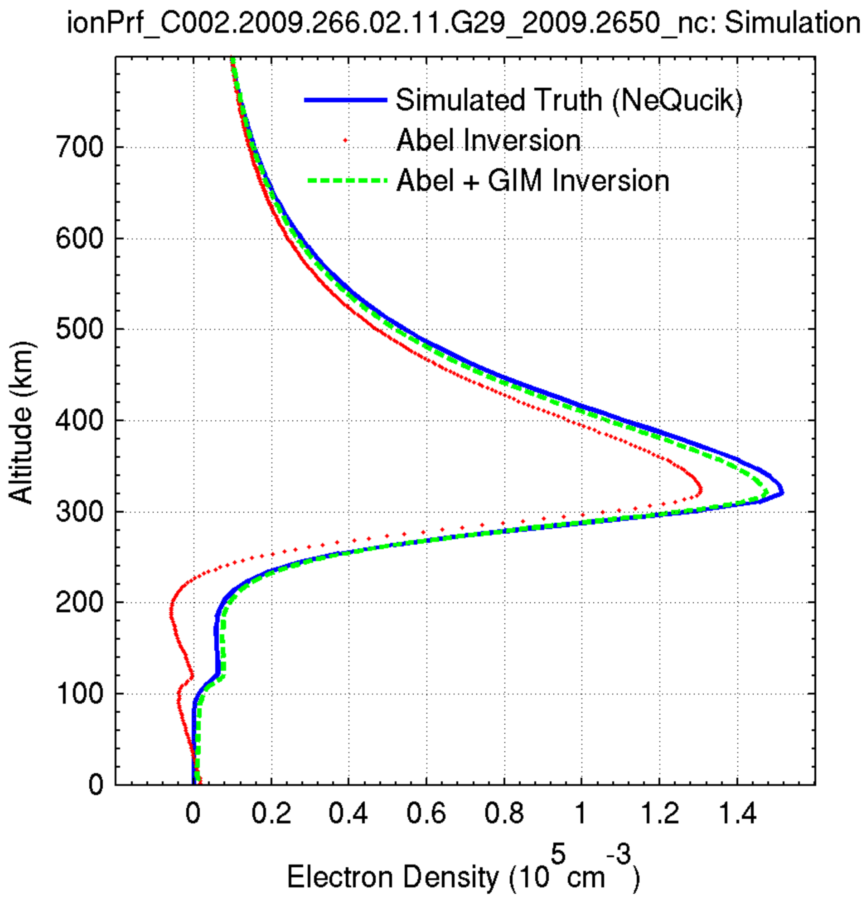
- The horizontal gradients of GIM are incorporated into the Abel inversion.

✓ Simulation:

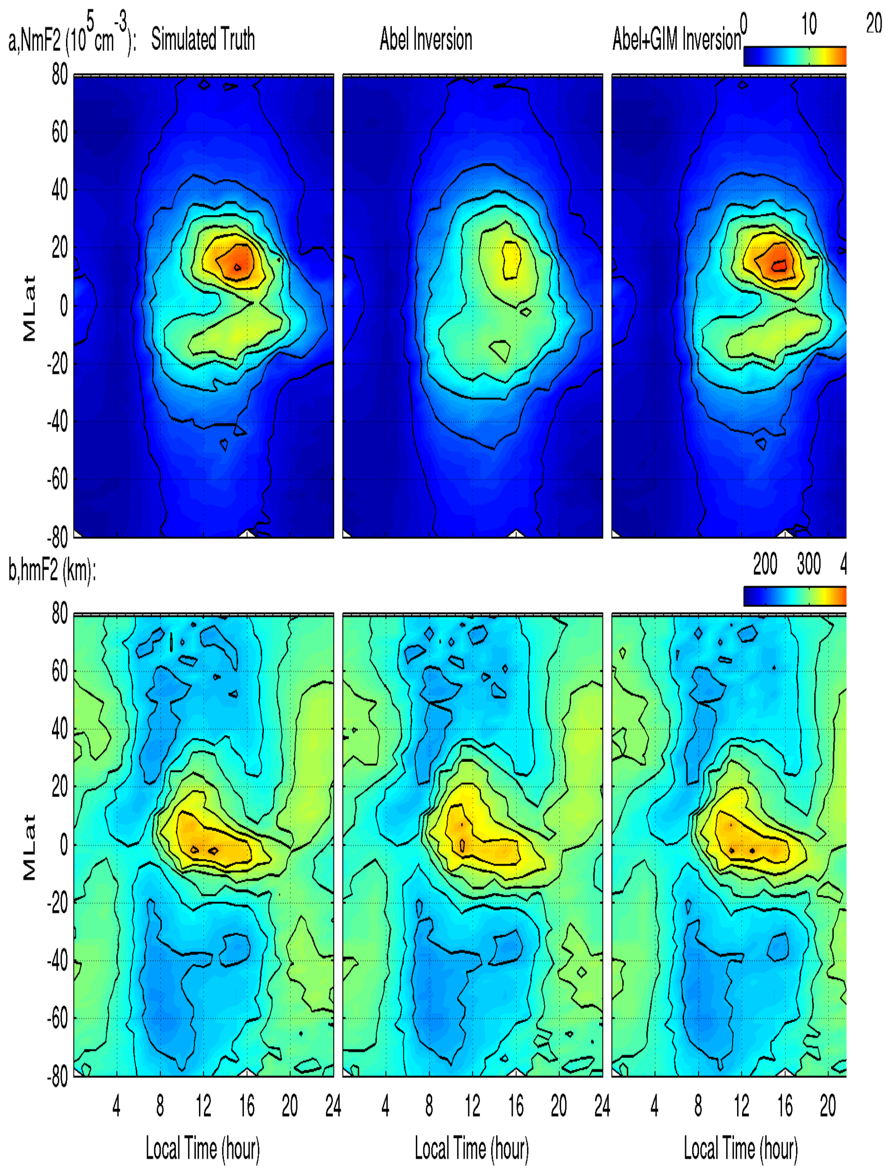
- COSMIC RO 2009.260-270.
- Simulation model: NeQuick.
- GIM: generated by NeQuick too.

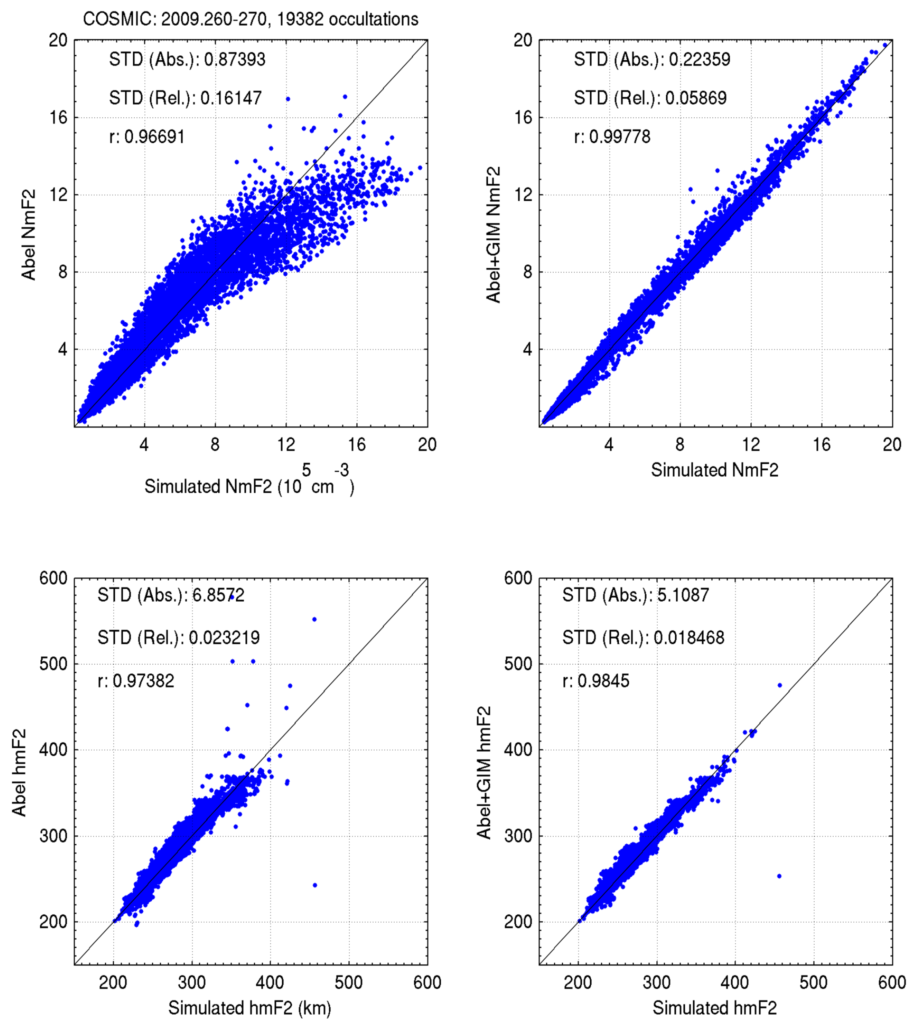
✓ Real data:

- COSMIC RO 2009.260-270.
- GIM: JPL GIM.



Simulation results (Sep.): NmF2 & hmF2:





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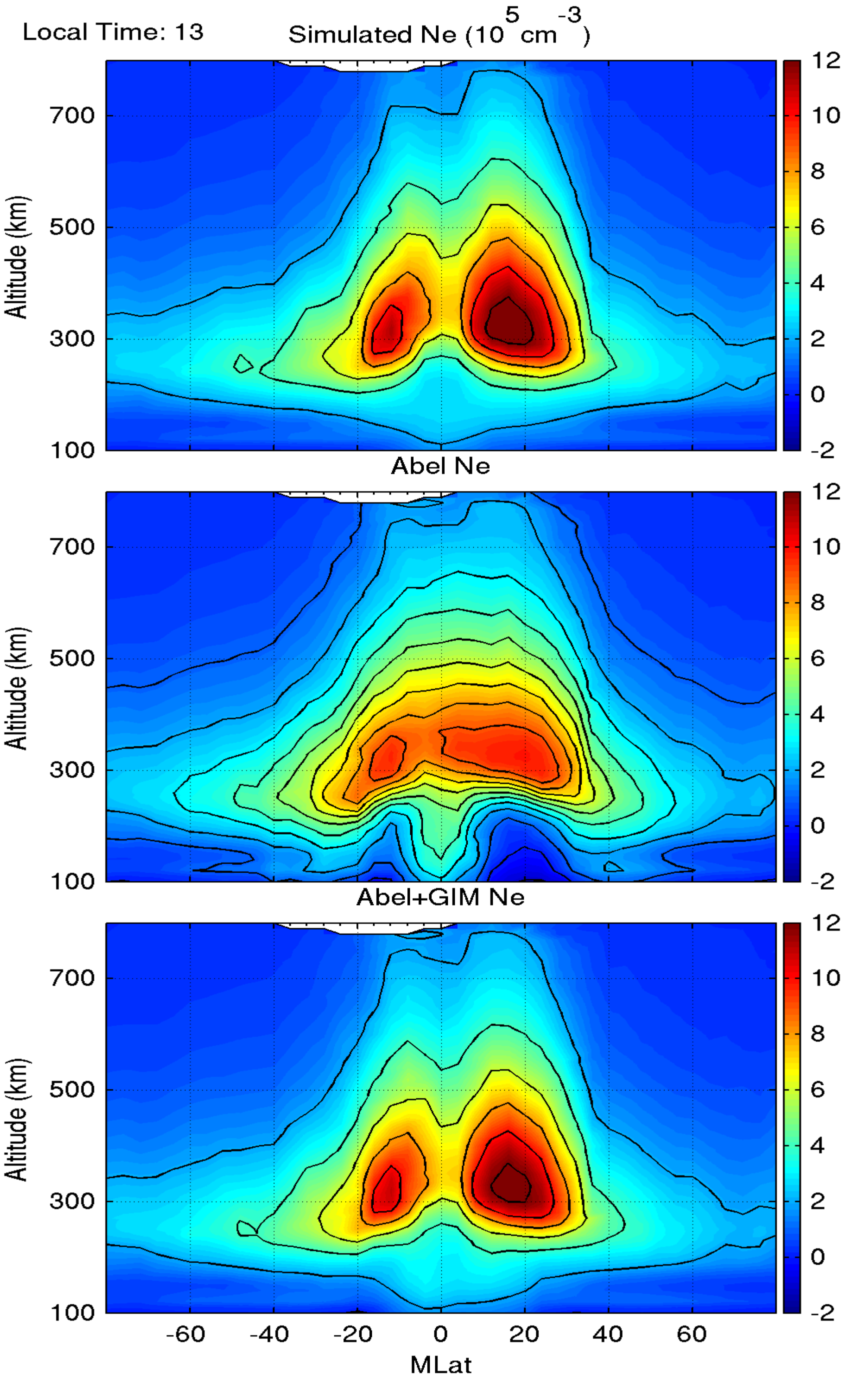
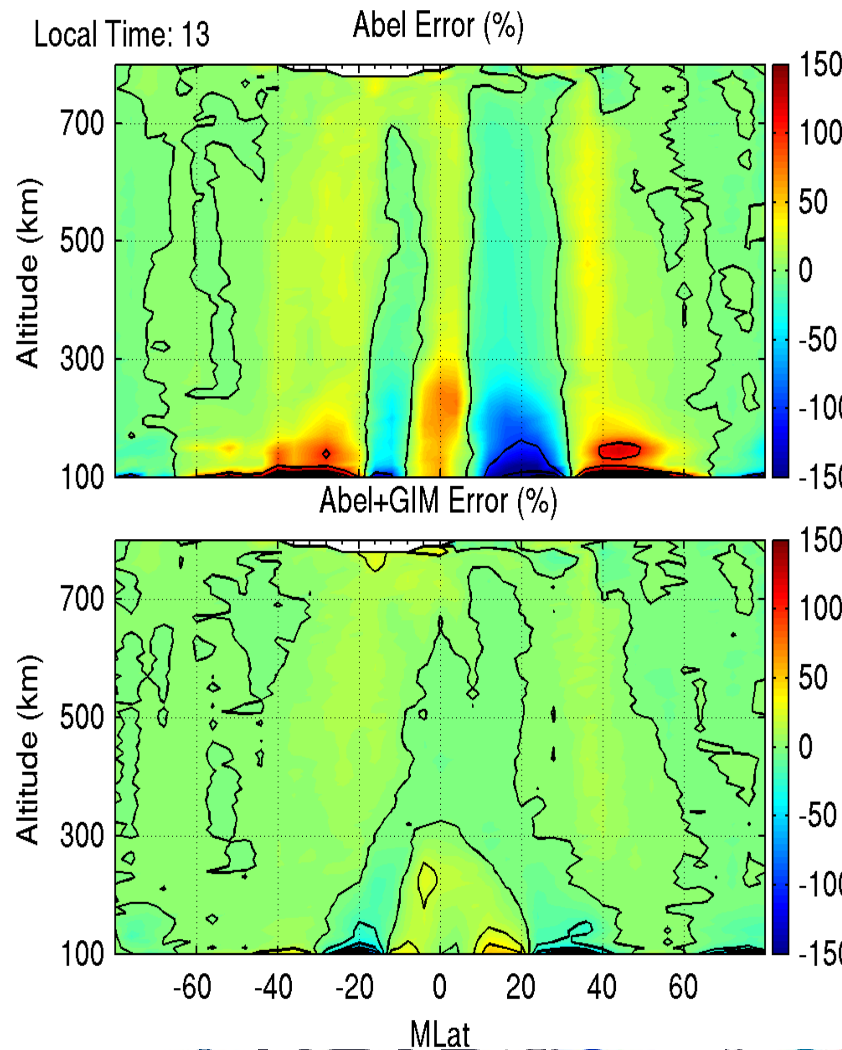
Simulation results: Ne, 13 LT





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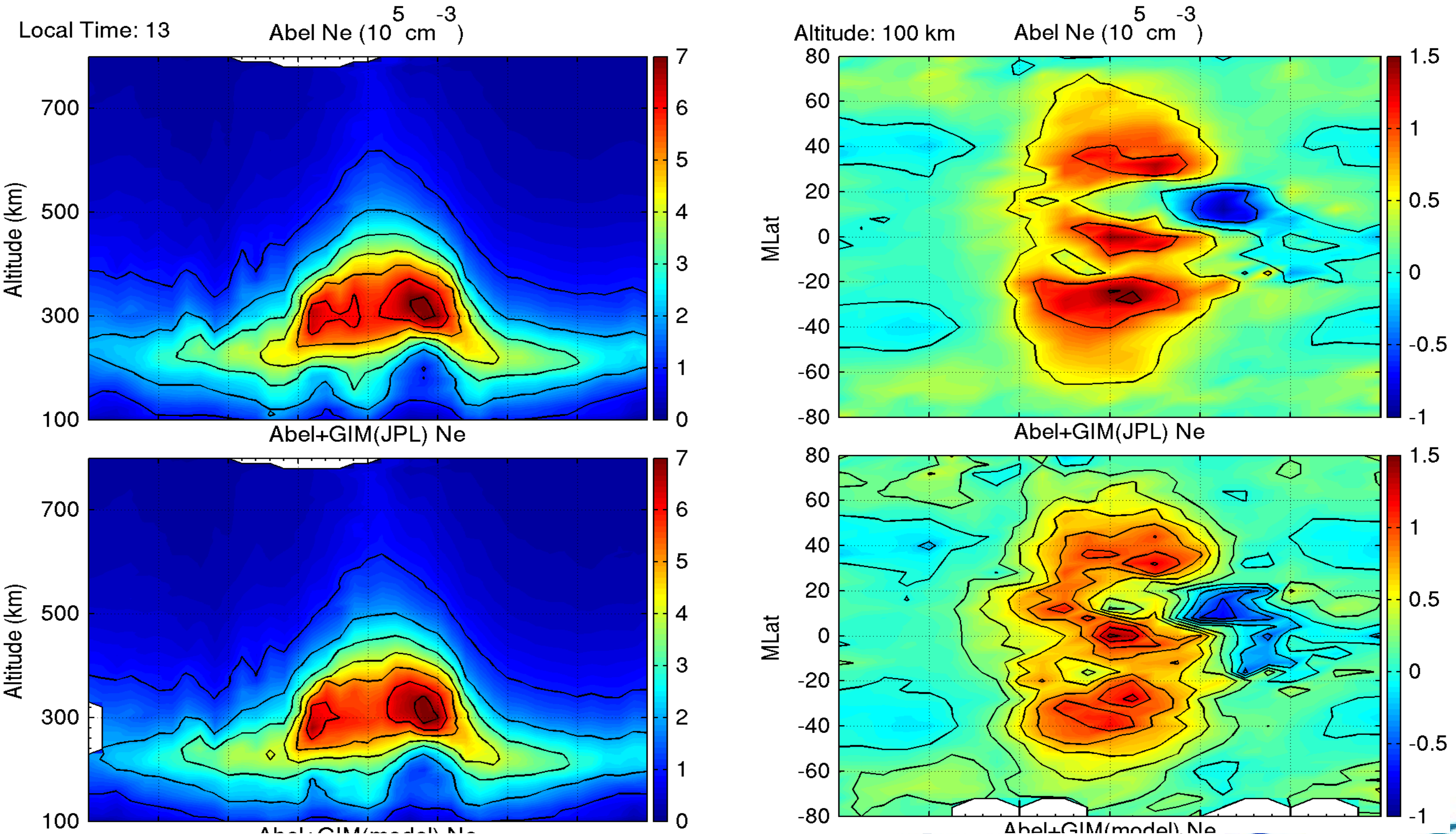
Real COSMIC Ne: Ne, 13 LT

Abel + GIM still has large-scale deviation,

reason: the real GIM is also based on the spherical symmetry assumption.



✓ RO electron density retrieval aided by ground based GNSS slant TEC:

- **Simultaneous global assimilation of ground and LEO based slant TEC into the model. The observations will provide horizontal gradient themselves. No assumptions needed. Should give high accuracy electron density along the tangent points.**

- **Especially for COSMIC 2 (and other missions of opportunity, more RO satellites, more GNSS satellites in the future), >500 RO events during ~1 hour.**

- **Need to do:**

  1, Build a global ionosphere data assimilation model.

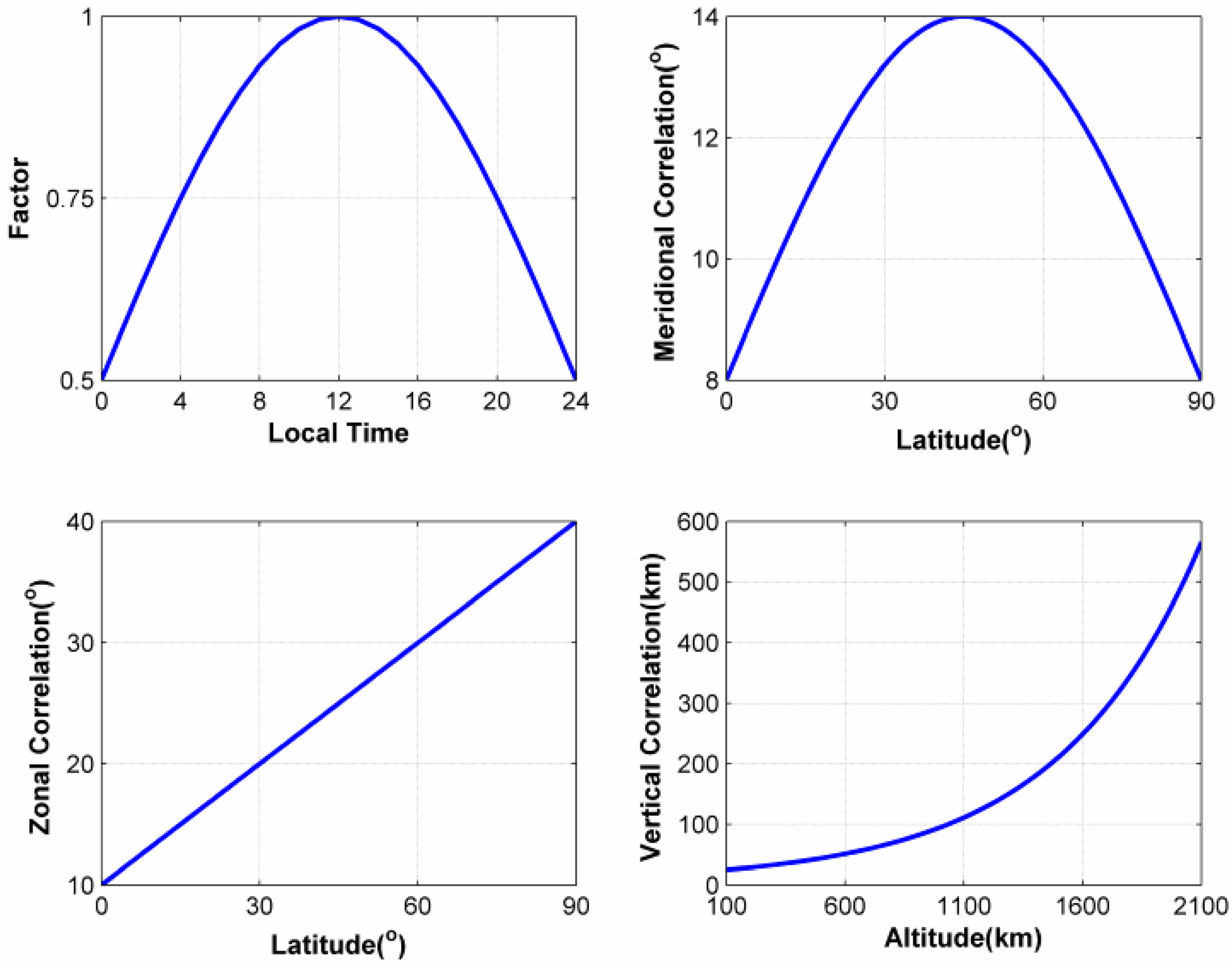
  2, Process ground based GNSS slant TEC.

  3, Process LEO slant TEC.

Key parameters of the assimilation model

- **Background model:** empirical model (NeQucik, IRI), not implement theoretical mode yet, easy to add other models
- **Space Resolution:** flexible, 2.5 latitude, 5 longitude, 20 km altitude in this study.
- **Background correlation and error:** Gauss correlation, cutoff when dlat>5, dlon>10, and dalt>40; square of background Ne.
- **Observation correlation and error:** un-correlated; 1% of background error.
- **Time resolution:** flexible, 1 hour in this study.
- **Altitude range:** flexible, 80-2000 km in this study, plasmasphere is calibrated by a simple H+ model.
- **Solve method:** Kalman Filter.
- **Storage:** sparse matrix method to save memory.
- **Inversion of innovation covariance:** restarted GMRES (generalized minimal residual) iteration method.
- **Computation power:** personal computer, 4 3.2 GHz cpus with 16 G memory.
- **Time cost:** ~ 20 minutes to get a global solution (~200,000 GNSS rays assimilated during 1 hour in this study, except background model calculation).
- **Input:** GNSS rinex files, IGS GIM, LEO orbit, GNSS orbit, navigation of Glonass (to get the frequency number). flexible to add different kind observations.
- **Data re-sampling and quantity control:** flexible. TEC range restriction; remove duplicate GPS ray.
- **Output:** global 3-D grid electron density.

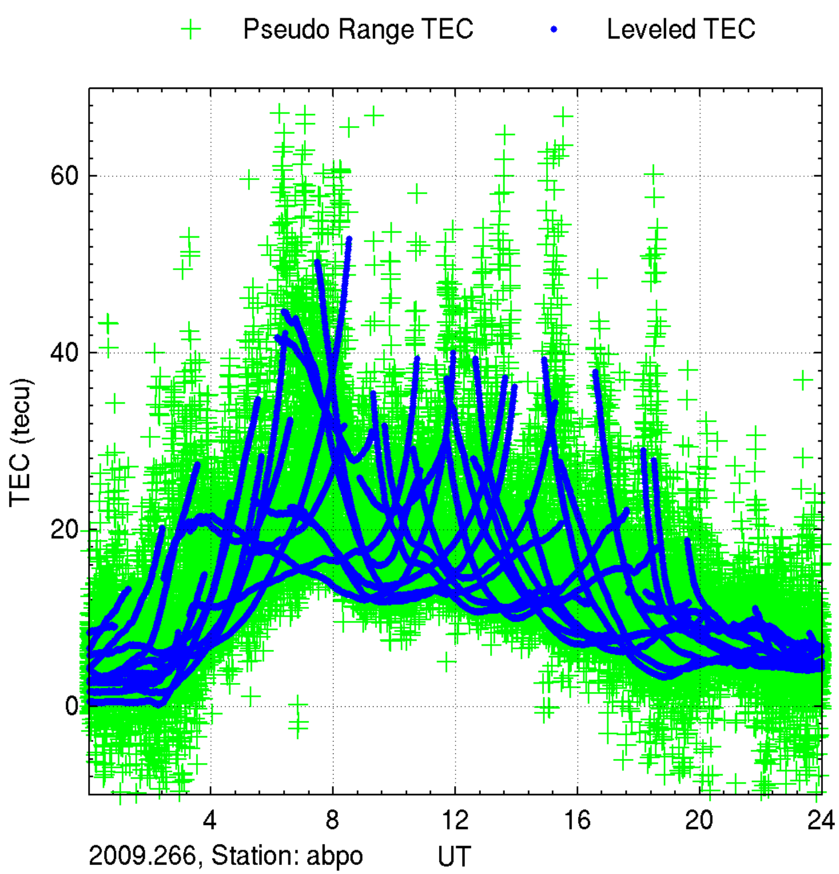
✓Ionospheric Correlation Length

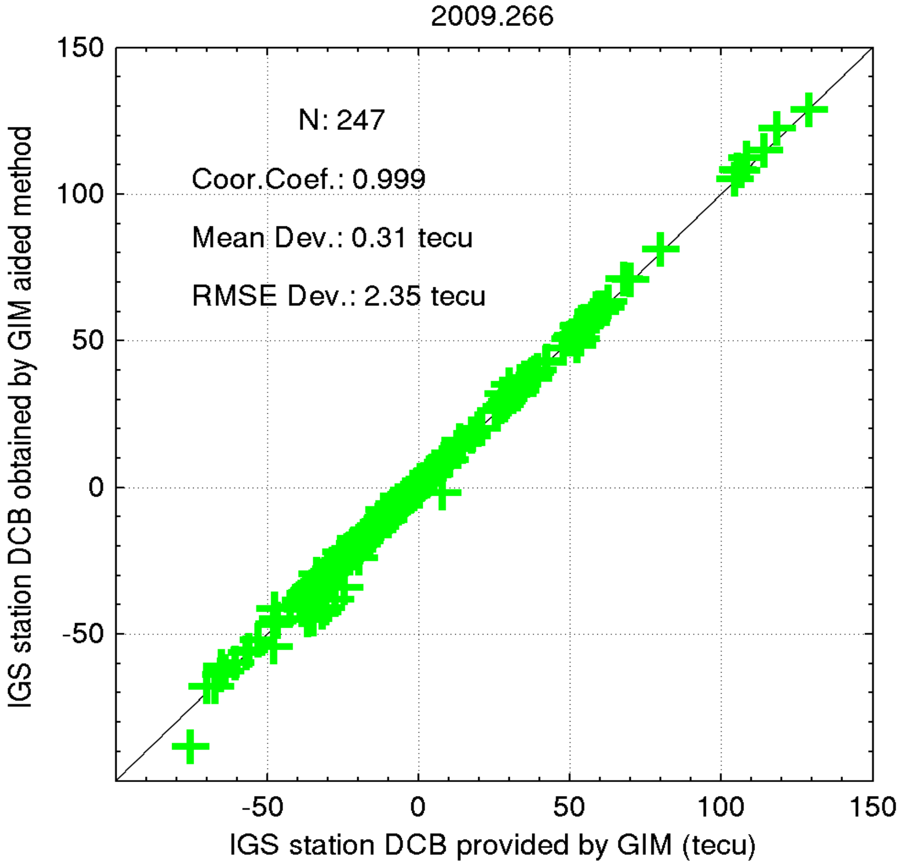


COSMIC

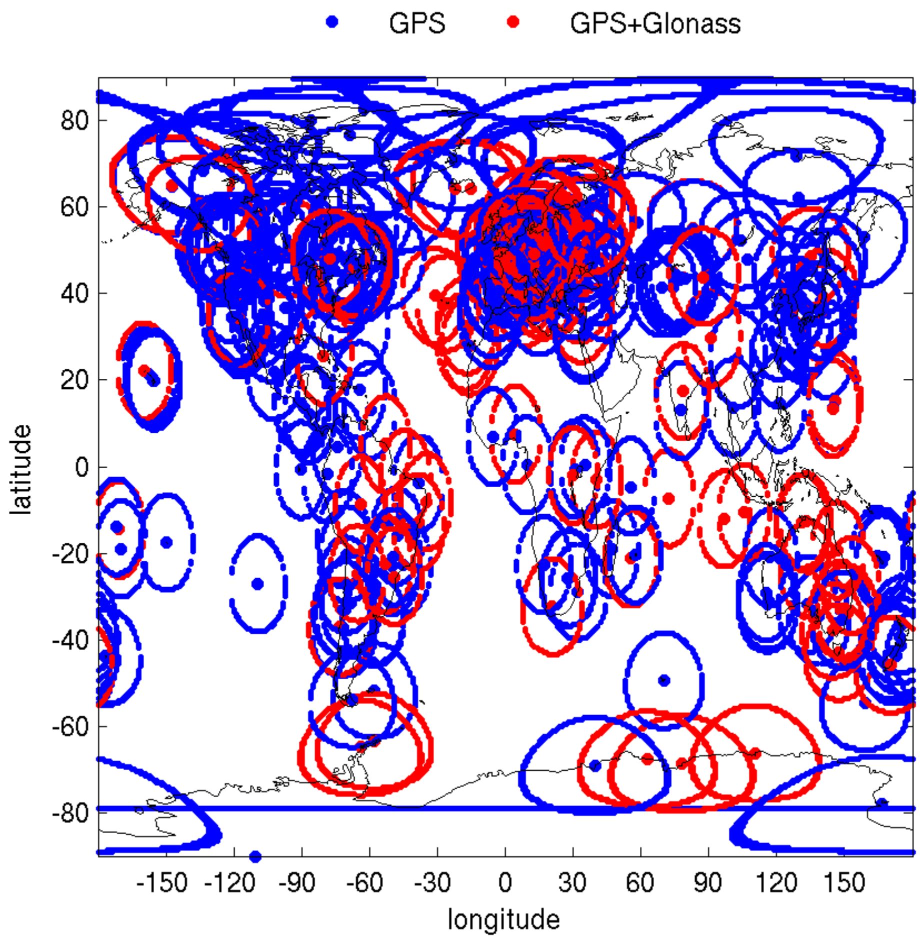
✓ **Ground based GNSS process mainly include:**

- **cycle slip detection;**
- **Leveling of phase TEC to pseudo-range TEC;**
- **Differential Code Bias (DCB) estimation: aided by IGS GIM**





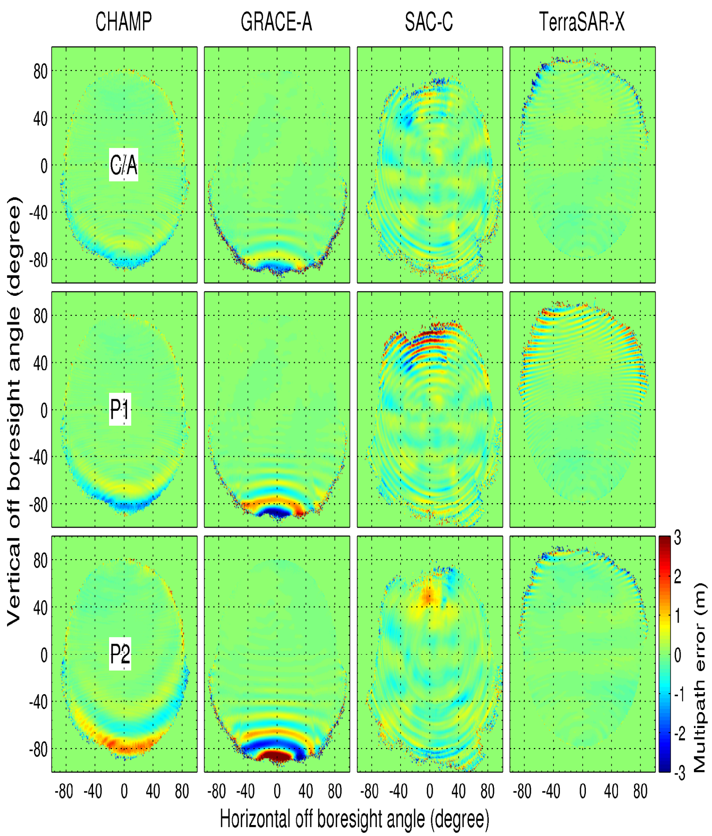
- ✓ Ground based GNSS observation, higher horizontal resolution than RO, good coverage over land.
- ✓ ~400 GNSS stations in IGS data center;>2000 + other data centers; 1/3 can observe both GPS and Glonass.



Left: IGS GNSS stations during 2009.266; >10 degree elevation coverage

✓ LEO based GNSS process mainly include:

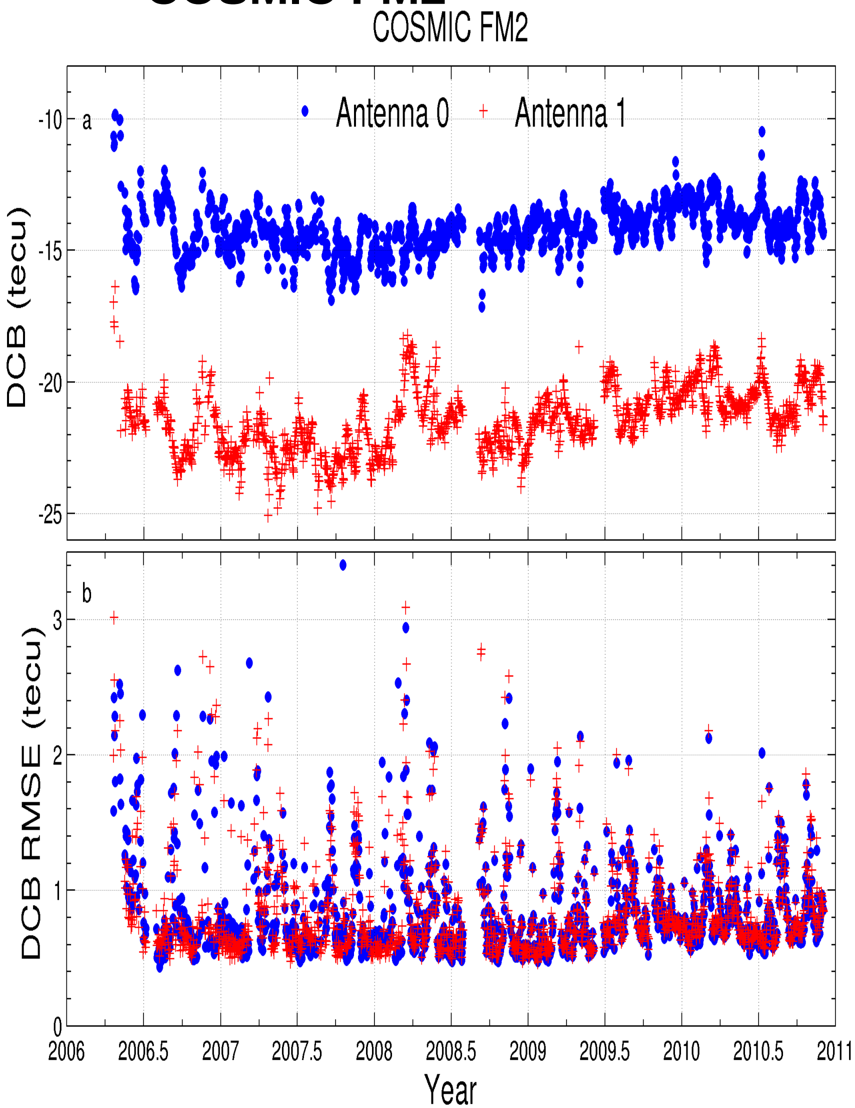
- cycle slip detection;
- **Multi path calibration;**
- Leveling of phase TEC to pseudo-range TEC;
- **Differential Code Bias (DCB) estimation: spherical symmetry assumption**



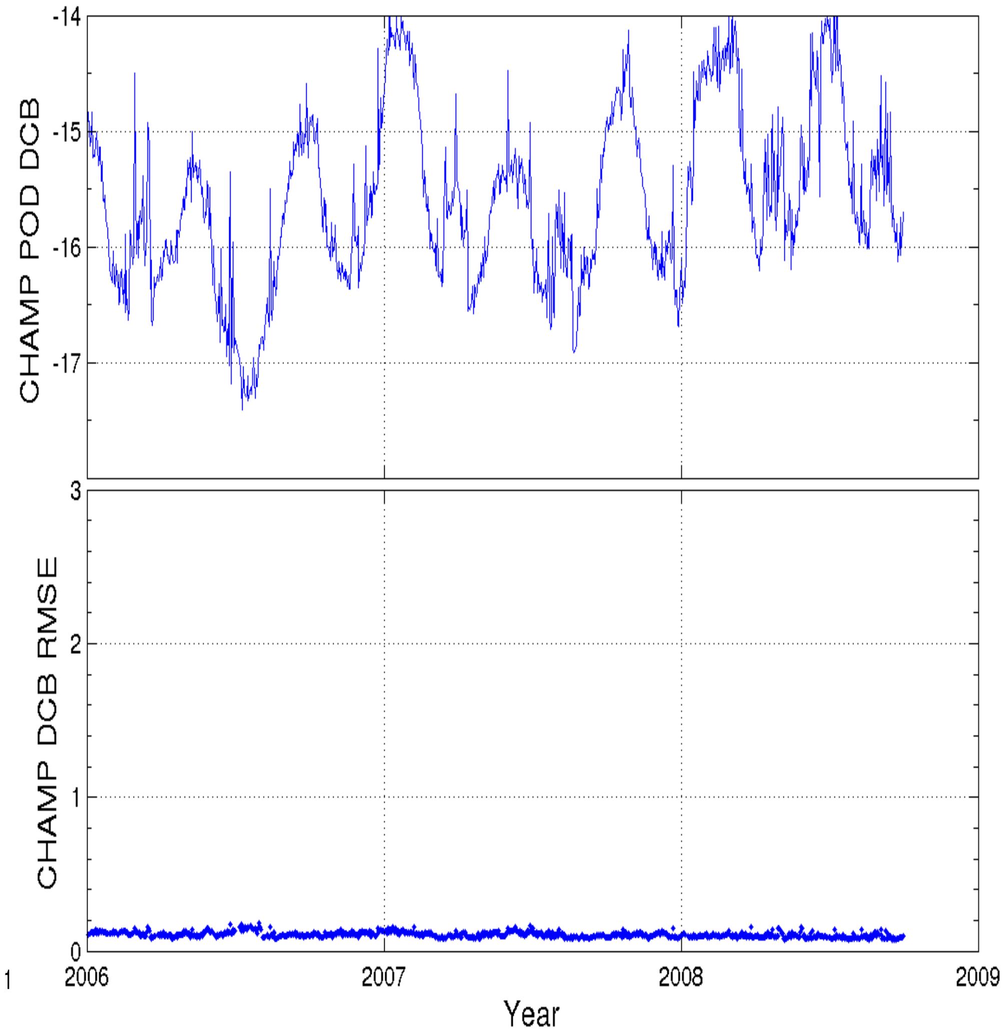
Mission	Inclination (°)/Altitude(km)/mass(kg)	GPS Receiver type	Operation years	POD antenna normal	Multipath RMSE (C/A, m)	Leveling error mean (tecu)	DCB RMSE mean (tecu)
COSMIC FM4	72/700-800/70	Blackjack	2006-	75° off the zenith	0.30	0.12	0.69
CHAMP	87.3/460-330/522	Blackjack	2000-2009	zenith	0.20	0.19	0.11
GRACE-A	89/~495/432	Blackjack	2002-	zenith	0.42	0.31	0.14
SAC-C	98.2/~710/467	Blackjack	2000-	zenith	0.42	0.60	0.87
TerraSAR-X	97.44/~514/1230	IGOR	2007-	zenith	0.29	0.15	0.09
Metop-A	98.7/~820/4093	GRAS	2006-	zenith	0.15	0.09	0.16

✓ Comparison of COSMIC and CHAMP POD DCB and RMSE:

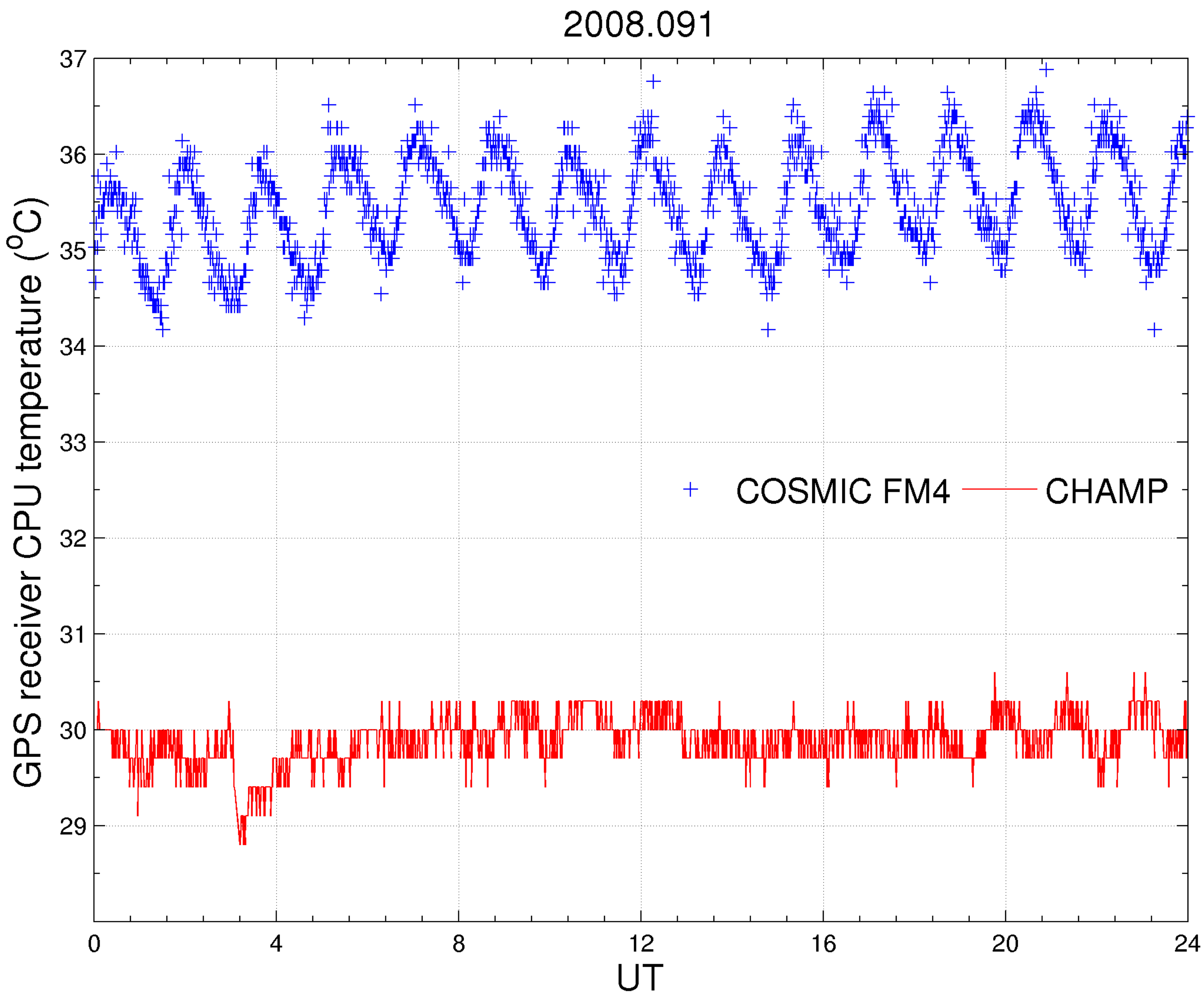
COSMIC FM2



CHAMP



✓ **Possible reason: receiver temperature variations influence the daily constant DCB assumption.**



✓ Assimilation (both simulation and real data test) setup in this study:

- Day: 2009.266. COSMIC. (~ 1100 occultations after quality control)
- 2.5 degree, 5 degree, 20 km grid;
- Input data: COSMIC RO: 1 second re-sampling; IGS GNSS: 1 minutes re-sampling (3.5 M IGS GNSS ray and 2.8 M COSMIC RO GNSS ray)

✓ Simulation:

- suppose all ~1100 occultations occur simultaneous.
- Simulation model: NeQuick (F107);Background: IRI (F107+40)

✓ Real data:

- Use Real configuration; assimilation hourly.
- Background model: IRI (F107)

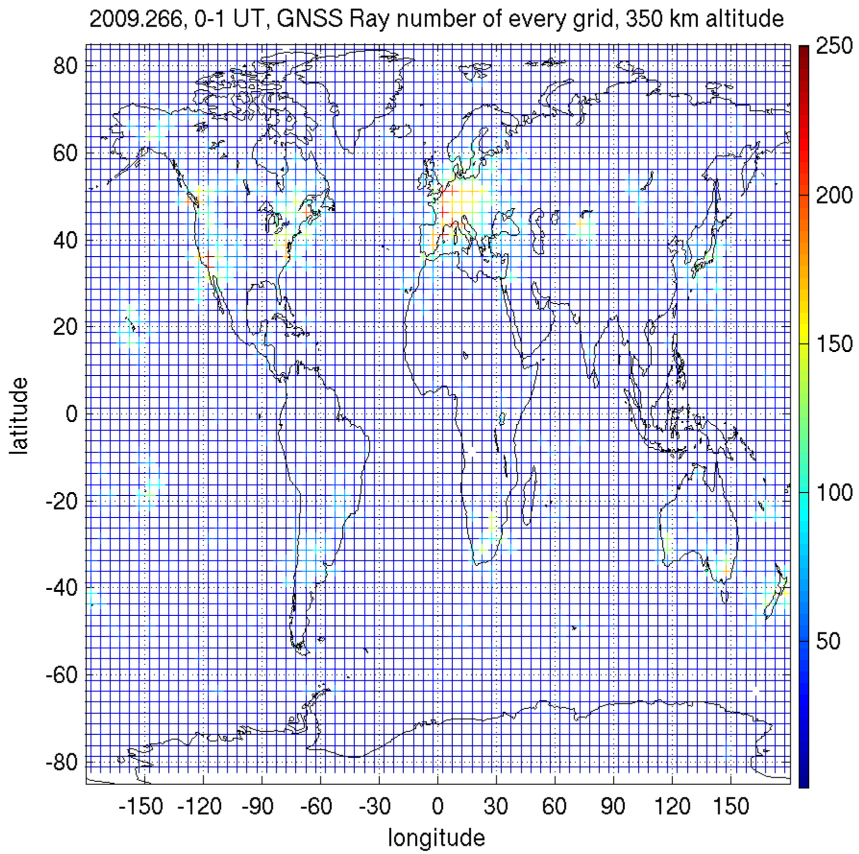
✓ Evaluation:

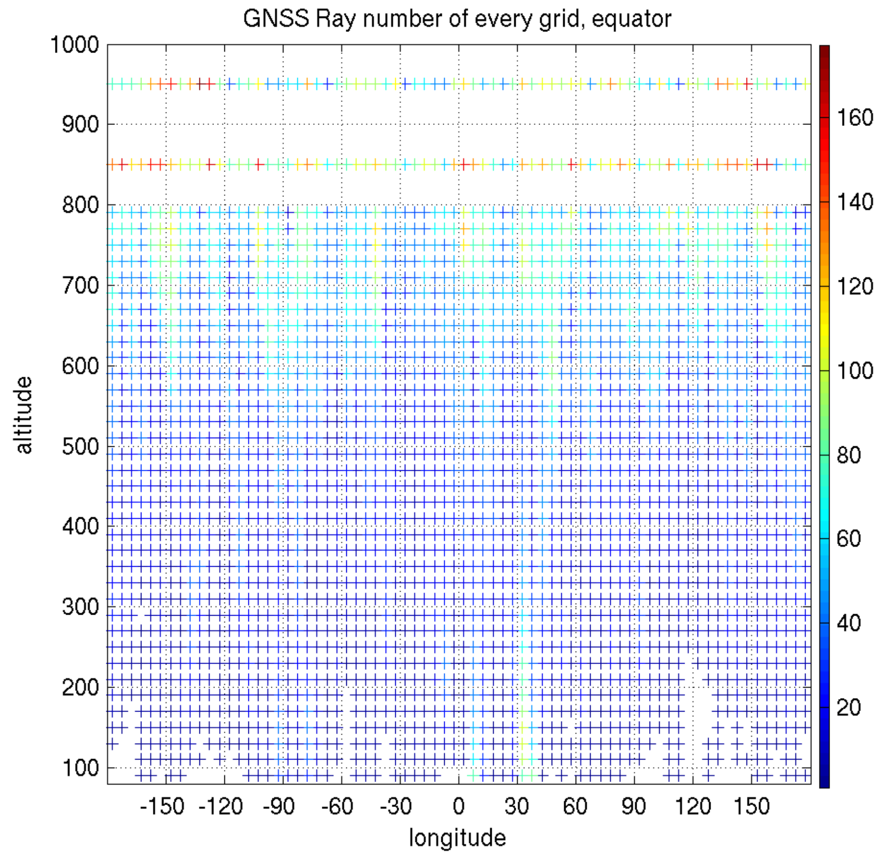
- Interpolate the after assimilation electron density to the tangent point of radio occultation events, compare with the Abel retrieved results for both simulation and real data test.

Simulation results:

Left: GNSS ray number around 350 km (2.5 by 5 by 20 km).

Right: GNSS ray number around equator





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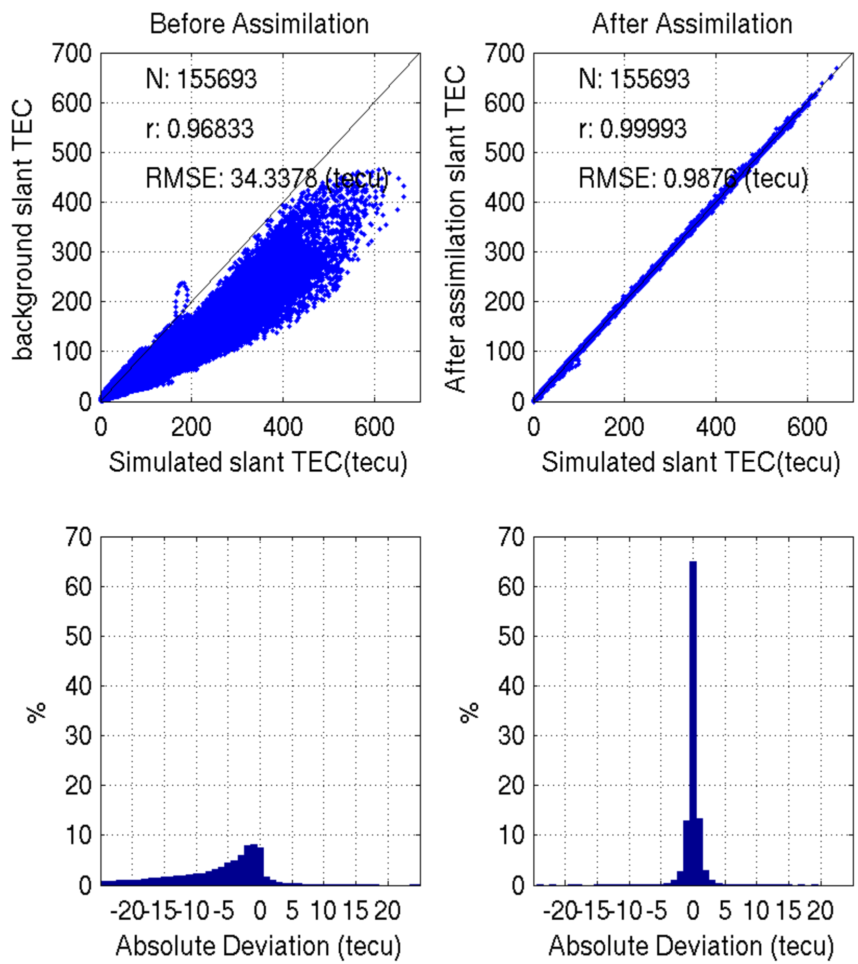
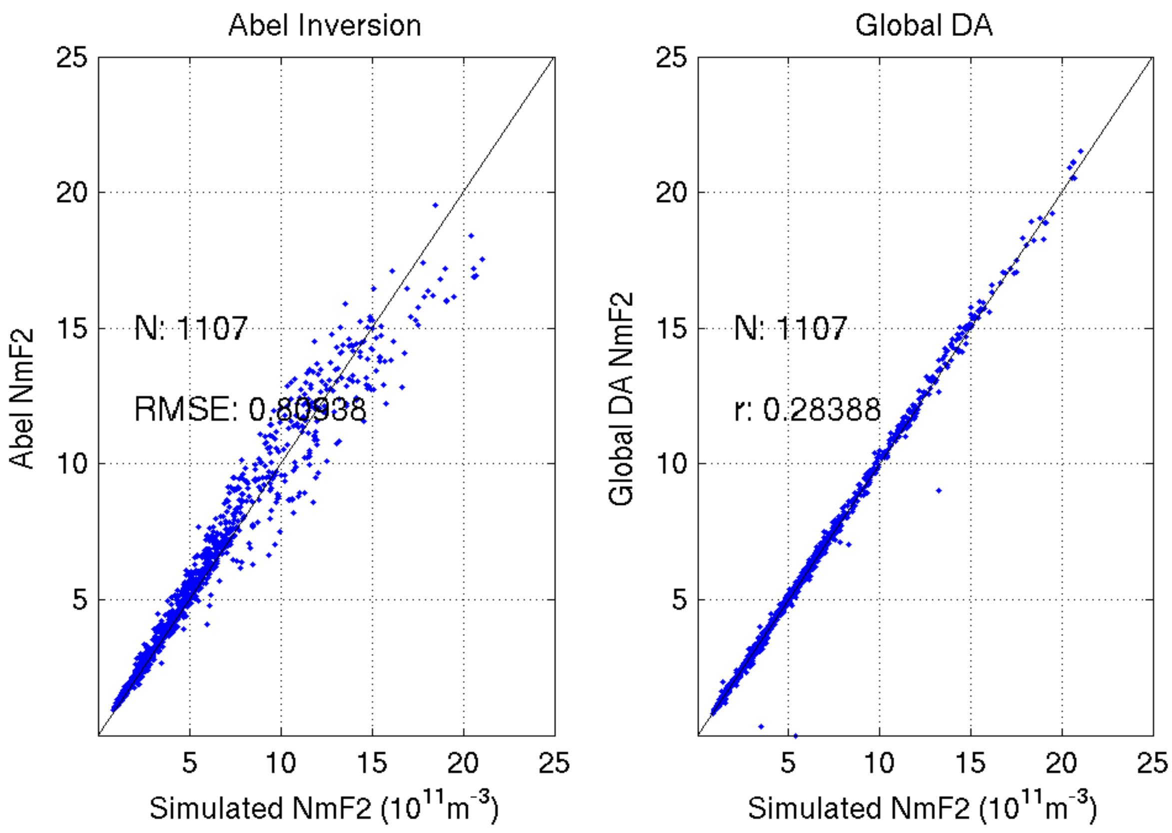
Simulation results:

Compare the slant TEC along the GPS ray before and after assimilation



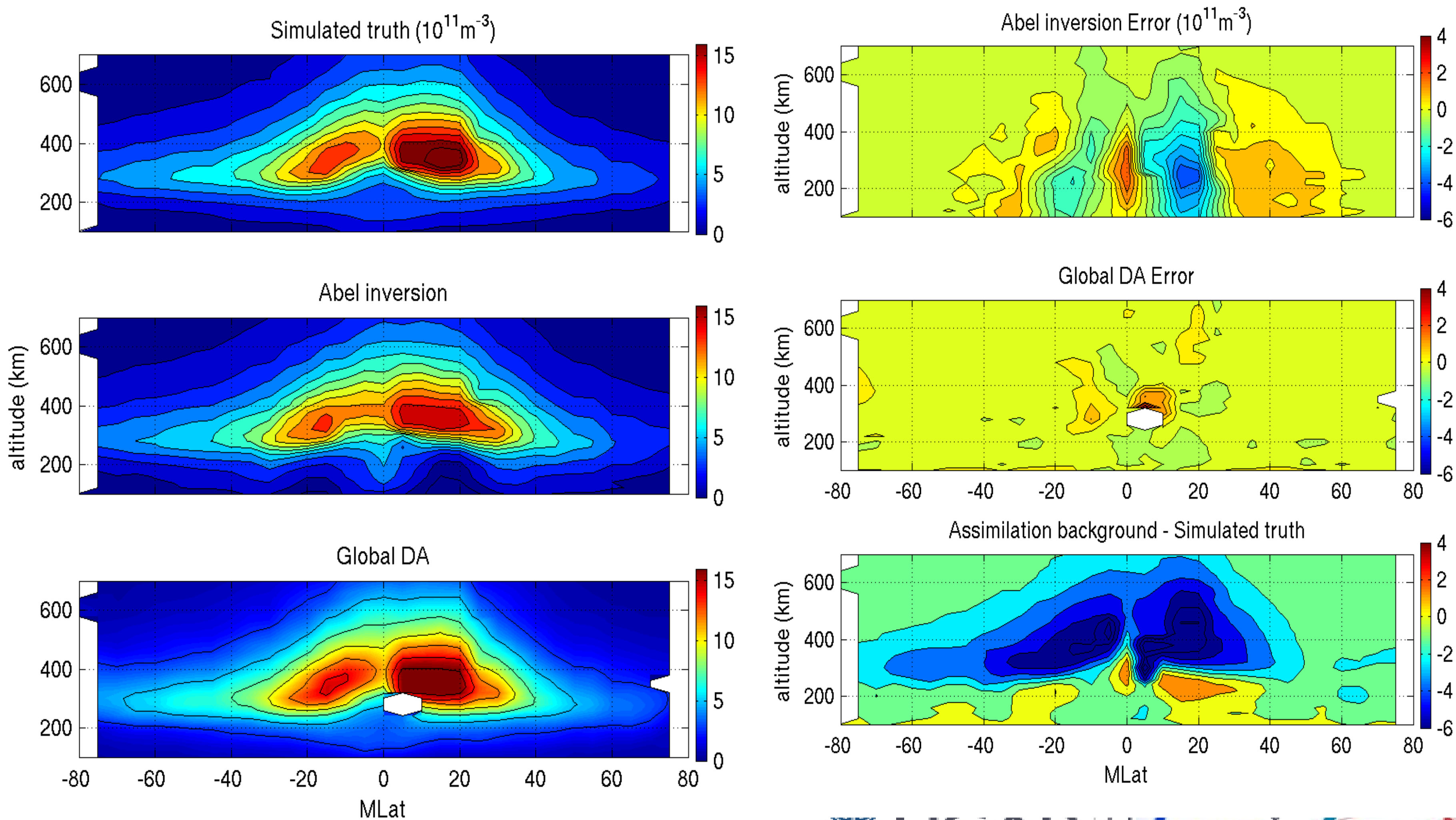
Simulation results:

Compare NmF2 for the occultations before and after assimilation



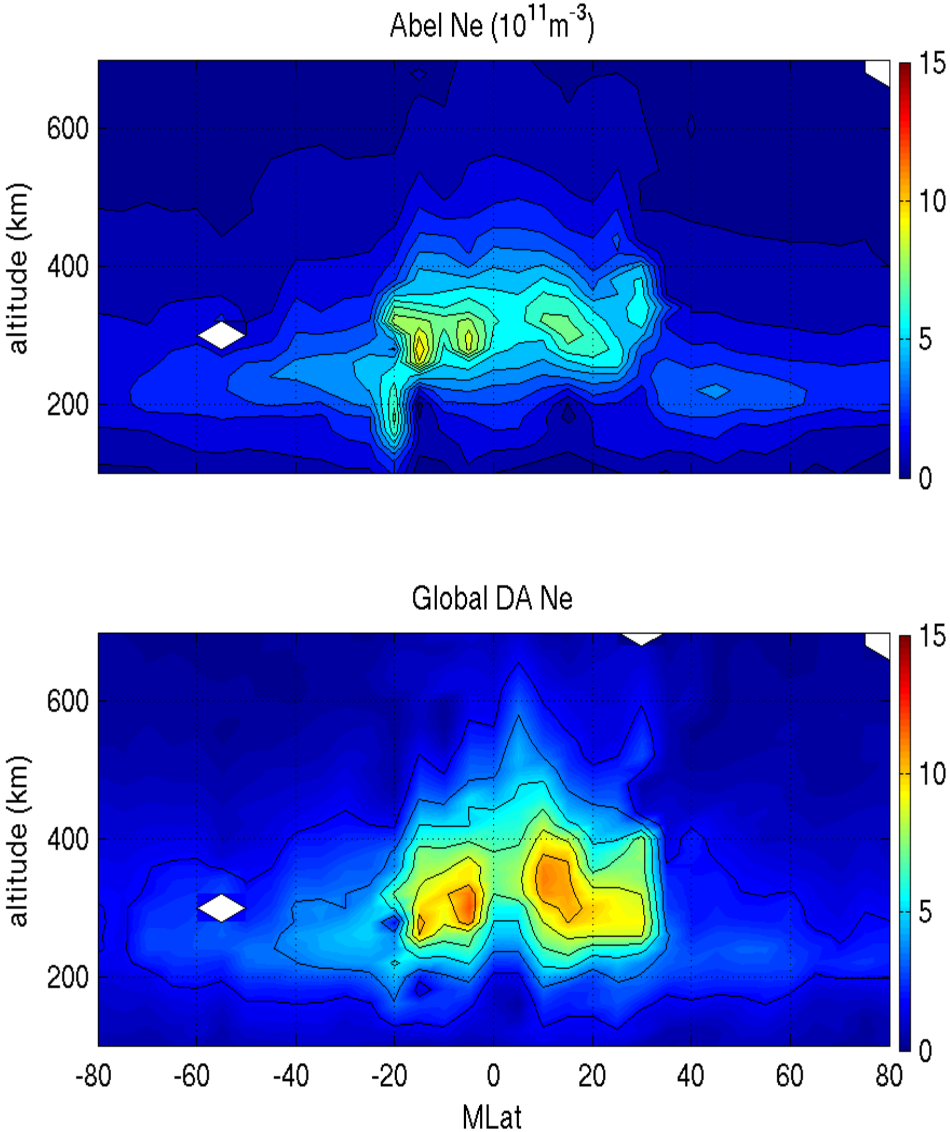
Simulation results:

Compare Ne and Ne error, 13 LT, only Ne along the tangent points are interpolated and compared.



Real data global data assimilation results:

Compare Ne, 13 LT, only Ne along the tangent points are interpolated and



Similar large-scale structure

Large scale deviations (like plasma cave) are improved by data assimilation.

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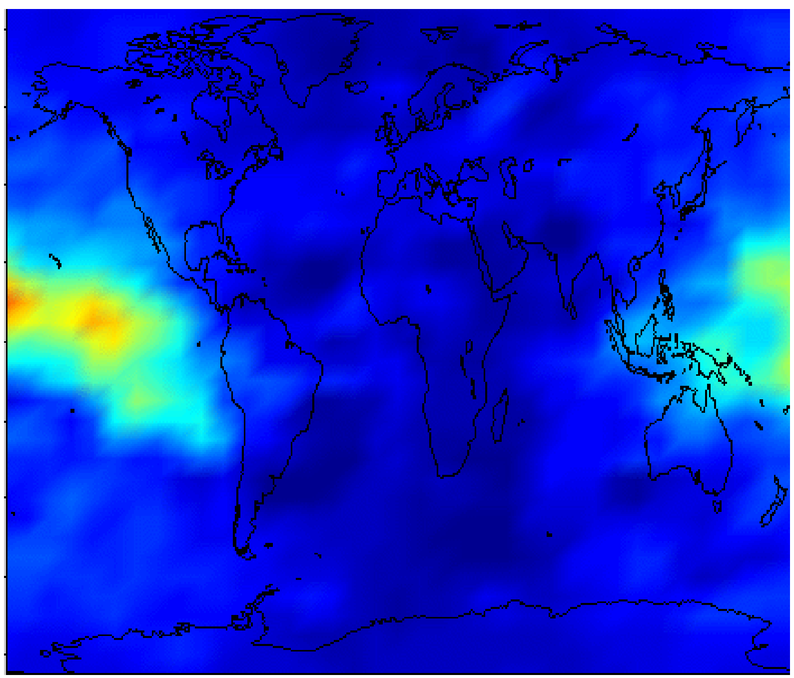
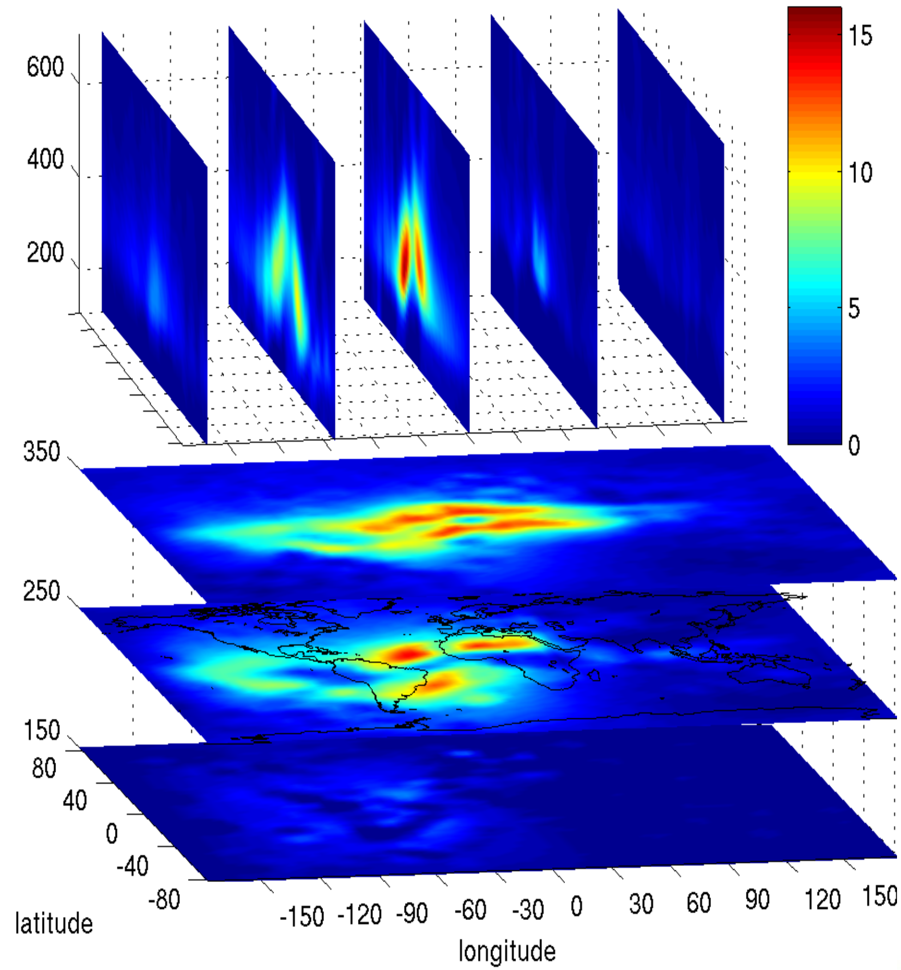
Real data global data assimilation results:
Left: hourly GIM; Right: Global 3-D Ne, 17 UT.





Conclusion:

✓ Standard Abel inversion:

- Reasonable results in topside, F region.
- Relative larger error in low altitude and low latitude region

✓ Abel inversion aided by GIM:

- Simulation results show good improvement.
- Real data test show large scale deviation too, because the real GIM is constructed based on the spherical symmetry assumption too.

✓ Global assimilation inversion aided by ground slant TEC:

- Simulation results show good performance either in F or E region.
- A possible method for COSMIC-2.
- Generate high level data product: global 3-D Ne