Radio occultation electron density retrieval aided by:

1. Ground based GNSS observations +
2. Global ionospheric data assimilation model

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Abel inversion and Error evaluation

RO inversion aided by ground GNSS and data assimilation model:

1. Ground & LEO GNSS process
2. Data assimilation model
3. Simulation results
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. [because of insufficient horizontal information].
Abel Error distribution versus latitude and altitude: Modeling results, Spring Equinox

Noon time LT=13

Unit: $1 \times 10^{11}/m^3$
COSMIC observations (same time/duration as simulation):

110 km

220 km

Abel retrieval from NeQuick model

Unit: $1 \times 10^{11}/m^3$
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
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**
**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 Details

<table>
<thead>
<tr>
<th>Mission</th>
<th>Inclination (°)/Altitude (km)/mass (kg)</th>
<th>GPS Receiver type</th>
<th>Operation years</th>
<th>POD antenna normal</th>
<th>Multipath RMSE (C/A, m)</th>
<th>Leveling error mean (tecu)</th>
<th>DCB RMSE mean (tecu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COSMIC FM4</td>
<td>72/700-80 0/70</td>
<td>Blackjack</td>
<td>2006-2007</td>
<td>75° off the zenith</td>
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</table>
Satellite environmental temperature effects on the Differential Code Bias (DCB) estimation: CHAMP DCB drift aggress well with orbit neutral temperature variation
Key parameters of the global ionospheric data assimilation model used in this study

- **Background model:** empirical model (NeQuick, IRI), easy to add other (theoretical) models
- **Space Resolution:** flexible, 2.5 latitude, 5 longitude, 20 km altitude in this study.
- **Background correlation and error:** Gaussian correlation, cutoff when dlat>10, dlon>20, and dalt>60; 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.
- **Inversion of innovation covariance:** restarted GMRES (generalized minimal residual) iteration method.
- **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 down-sampling and quantity control:** flexible. TEC range restriction; remove duplicate GPS ray.
- **Output:** global 3-D grid electron density.
Simulation:

- Suppose ~1100 occultations during 2009.266 occur simultaneously.
- Simulation model: NeQuick (F107); Background: IRI (F107+40)
- Assimilate these occultations and ground based GNSS observation into the model

Evaluation:

- Interpolate the electron density after assimilation to the tangent point of radio occultation events, compare with the corresponding Abel retrieved results.
Simulating the improved effect of global data assimilation on the electron density retrieval (compared with Abel inversion):

**left:** NmF2 comparison

**right:** Error comparison
Conclusion:

- Global assimilation inversion aided by ground slant TEC:
  - Simulation results show good performance either in F or E region. Less systematic error than Abel inversion.
  - A possible method for COSMIC-2.[sufficient data are available]
  - Generate high level data product: global 3-D Ne