Use of Radio Occultation Data in Ionospheric Assimilation Algorithm (IDA4D)

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Thanks to:
Gary Bust, APL
Fabiano Rodrigues, UTDallas
Mike Nicolls, SRI
REALTIME SPACE-WEATHER:
ASTRA Space Weather App
ASTRA Overview

- **Spaceweather Modeling**
- **Data Assimilation**
- **Data Analysis**
- **Instrument Development**
- **Space Systems**

- **TIMEGCM**
- **AMIE**
  - High-latitude Electrodynamics
- **IDA4D**
  - Global Ionosphere

- **Space Based Data**
- **Ground Based Data**
- **HF TID Mapper**
- **GPS-based Space Weather Monitor**
- **Fabry-Perot Interferometer**
- **Space weather Phone Apps**

- **NSF DICE CubeSat**
- **SMC SENSE**
- **Plug-N-Play Avionics**
- **Scanning Photometer System**
- **Space-based GPS receiver**
- **Temperature Sensor (Balloon) & Dosimeter**
Outline

• Description of IDA4D
  – History of Radio Occultations in IDA4D
  – Example results

• Using IDA4D to improve E-region density retrievals
  – Method
  – Low-latitude climatology
  – High-latitude conductances

• Simulation: GEOScan 66 Satellite Radio Occultation
• Simulation: CubeSat RO vs UV
• Summary
Ionospheric Data Assimilation Four Dimensional.IDA4D

- Global 3D time-evolving imaging of the ionosphere electron density
  - Gauss Markov Kalman Filter predicts forward in time

- **Solves for log of electron density**
  - Guarantees positivity
  - Errors are more log normal distribution

- **Completely irregular horizontal grid, vector of vertical grid points**
  - User selectable
  - High resolution where desired
  - Can be dynamically chosen based on data

- **Configuration files**
  - User configurable error covariance
  - Model of background ionosphere
  - Amount of and type of data
  - Regional/global
  - Time steps
  - Convergence criteria
  - Data sampling rates, averaging windows, sampling windows, data representation errors
IDA4D and Radio Occultations

- IDA4D has routinely ingested slant TEC from Radio Occultations since 2002.
  - Slant TEC between LEO receiver and GPS transmitter
  - *not* Abel inverted Ne profiles

- IDA4D has ingested RO TEC from:
  - PICOSat, IOX, CHAMP, SAC-C, GRACE and COSMIC

- Typical case with CHAMP, GRACE and 6 COSMIC: April 1, 2007
  - 15 minute cadence for IDA4D analyses
  - 5 second averaging on occultation TEC
  - ~ 4000-5000 RO-TEC observations per 15 minute analysis
### Example RO for 1 UT on April 1, 2007

#### Altitude (km)

<table>
<thead>
<tr>
<th>LAT</th>
<th>63</th>
<th>57</th>
<th>51</th>
<th>45</th>
<th>37</th>
<th>31</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEC (TECU)</td>
<td>600</td>
<td>400</td>
<td>200</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### RO-DATA

- OCC Comparison for 01:00 UT Occ #: 004
- IRI
- IDA
- RO-DATA

#### VTEC

- Color Bar: 1.0 to 40.0
- Map of VTEC (TECU)

#### Electron Density (10^11 el/m^2)

- Color Bar: 0.0 to 6.5
- LAT 63 57 51 45 37 31 25
The radio occultation technique

Now, if the distribution of electron density \( n_e \) in the ionosphere were spherically symmetric, at least over the region we are interested, we could write:

\[
n_e(\text{lat, lon, } h) = n_e(r)
\]

And we can show that TEC\((h_t)\) would be given by the so-called **Abel transform**:

\[
TEC(h_t) = 2 \int_0^\infty \frac{n_e(r) r dr}{\sqrt{r^2 - h_t^2}}
\]

Given TEC measurements, one can obtain \( n_e(r) \) using the **inverse Abel transform**:

\[
n_e(r) = -\frac{1}{\pi} \int_0^\infty \frac{d}{dh_t} TEC(h_t) \frac{dh_t}{\sqrt{h_t^2 - r^2}}
\]

Unfortunately (or fortunately for some of us), \( n_e(\text{lat, lon, } h) = n_e(r) \) does not hold in **most cases**, and horizontal density gradients should be taken into account when trying to obtain estimates of \( n_e(h) \) from RO TEC observations.
Estimating E-region profiles: An alternative approach

Assuming that spherical symmetry assumption only holds in the E-region we can write:

\[ TEC(h_t) = 2 \int_{h_t}^{150} n_e(r) r dr \sqrt{r^2 - h_t^2} + \int_{s_1}^{s_1^{150}} n_e(s_1) ds_1 + \int_{s_2}^{s_2^{150}} n_e(s_2) ds_2 \]

The measured TEC has contributions from the E and F regions:

\[ TEC(h_t) = TEC_{E-region} + TEC_{F-region} \]

And the E region TEC can be obtained from:

\[ TEC_{E-region} = TEC(h_t) - TEC_{F-region} \]

- \( TEC(h_t) \) are the RO measurements
- \( TEC_{F-region} \) can be obtained from assimilative model (we use IDA4D)
- \( n_e(h) \) can be obtained from \( TEC_{E-region} \)
Validation versus Radar Measurements

Validation/Comparison Analysis

Nicolls et al. (2009)
Statistical/Climatological Results

Ne vs Local Time – Apr 2007 (-20° < lat < 20°)

• Data – Mean – Median

Nicholls, Bust and Rodrigues, 2009
Polar E-region Densities and Conductances
**GEOScan: Simulating 66 LEO satellites with RO**

- **66 Iridium Satellites in Polar orbit at ~ 780 km altitude**
- **Simulate RO TEC data for 3 hours**
  - November 20, 2003 Superstorm 15-18 UT
  - Use TIMEGCM simulation as “Ground Truth”
  - Fly all 66 satellites in actual Iridium orbital planes with correct geometry
  - Use actual GPS ephemeris for the day to get links between LEO Iridium receivers and GPS transmitters
  - Compute TEC using TIMEGCM “Truth”
- **IDA4D Inversions**
  - Use IRI as background model: *No mixing of “truth ionosphere” and background model in IDA*
  - Use ONLY RO TEC data. No ground GPS or any other kind of simulated data
  - Run for 3 hours, 5 minute cadences for IDA4D inversions
  - Do another run using only the actual ground GPS available for that day as a comparison
GEOScan Simulations

TRUTH

Ground-based GPS TEC

IRI

IDA4D
CubeSat Mission Simulations

• We performed simulations for 1 and 2 satellites in various orbital inclinations and altitudes.
• We simulated various scenarios with 1-2 instruments on each satellite – 650 km
• We quantified the performance against the simulated truth (again our old friend TIMEGCM November 20, 2003), and compared against ground GPS only as our baseline
• Scenarios
  – Ground GPS only
  – Ground GPS, Insitu electron density, Occultations
  – Ground GPS, Insitu electron density, Nadir 1356 Radiances (night only)
  – Ground GPS, Insitu electron density, Nadir 1356 Radiances (night only), Occultations
• Skill score used to quantify performance
  – Baseline is the ground GPS-only case.
CubeSat Simulations: Skill Score for VTEC Retrievals

Comparison of 15 Degrees Great Circle or Less off Track: Night Only

Comparison of 15 Degrees Great Circle or Less off Track: Day Only
CubeSat Simulations:
Skill Score for VTEC Retrievals

Comparison Along Satellite Track

Comparison of 15 Degrees Great Circle or Less off Track
DICE Langmuir Probe Data

Farkle 05/25/12

Plasma Density [m$^3$]

- IRI
- IDA4D
- LP

UTC

Lat.

Electrons / m$^3$

Local Time (Hours)

- 1.00e+10
- 2.08e+11
- 4.97e+11
- 6.05e+11
- 8.03e+11
- 1.00e+12
- 1.20e+12

Longitude (Degrees)

900
800
700
600
500
400
300

-90
-60
-30
0
30
60
90

(b) (c) (a)
Summary

- IDA4D has routinely ingested RO TEC for ~10 years.
- IDA4D results have been used for science studies, applications, and simulations.
- A novel approach of combining IDA4D with RO TEC leads to improved estimates of E-region densities.
- These E-region densities have been used to investigate low latitude climatology as well as high latitude conductances.
- A 66 satellite GEOScan simulation of only RO TEC shows that such a dense satellite data set can completely (nearly) recover the original electron density.
  - needs more work, varying number of satellites
  - seems capable of retrieving entire 3-D ionosphere, including horiz structure
- Other simulations for Cubesats have shown the performance improvements obtained by RO.
- Validation of DICE Langmuir Probe Data
Derivation of Skill Score Metric

\( D_i \) - IDA4D data point value

\( M_i \) - Baseline data point value

\( T_i, \nu_i^T \) - Truth data point value, Truth variance

\[
\psi_D^2 = \sum_i \frac{(D_i - T_i)^2}{\nu_i^T}
\]

\[
\psi_M^2 = \sum_i \frac{(M_i - T_i)^2}{\nu_i^T}
\]

\[
S = 1.0 - \sqrt{\frac{\psi_D^2}{\psi_M^2}}
\]