Use of Radio Occultation Data in Ionospheric Assimilation Algorithm IDA4D

Gary Bust, Geoff Crowley, Fabiano Rodrigues
ASTRA LLC
Boulder, CO

Mike Nicolls
SRI International
Menlo Park, CA
Spaceweather Modeling

Data Assimilation

Data Analysis

Instrument Development

Space Systems

TIMEGCM

AMIE High-latitude Electrodynamic

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

Science

Technology

Applications

Bringing It All Together

Space Weather and SSA
REALTIME SPACE-WEATHER: ASTRA Space Weather App
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) vs TEC (TECU)

IDA  RO-DATA  IRI

OCC Comparison for 01:00 UT Occ #: 004

01:00 UT UT

VTEC

01:00 UT

date = day 091 2007: IDA3D

01:00 UT

date = day 091 2007: IRI

Electron Density (10^16 el/m^2)
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 \textbf{Abel transform}:

\[
TEC(h_t) = 2\int_{h_i}^{\infty} \frac{n_e(r)rdr}{\sqrt{r^2 - h_t^2}}
\]

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

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

Unfortunately (or fortunately for some of us), \( n_e(\text{lat, lon, h}) = n_e(r) \) does not hold in \textbf{most cases}, and horizontal density gradients should be taken into account when trying to obtain estimates of \( n_e(h) \) from RO TEC observations.
Validation versus Radar Measurements

Validation/Comparison Analysis

Nicolls et al. (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 vs. IRI

Ground-based GPS TEC vs. 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
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 ionos, including horiz struc.
- Other simulations for Cubesats have shown the performance improvements obtained by RO.
Derivation of Skill Score Metric

\[ D_i \quad \text{- IDA4D data point value} \]
\[ M_i \quad \text{- Baseline data point value} \]
\[ T_i, \nu_i^T \quad \text{- Truth data point value, Truth variance} \]

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

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