Use of Radio Occultation Data in Ionospheric Assimilation Algorithm IDA4D

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ASTRA Overview

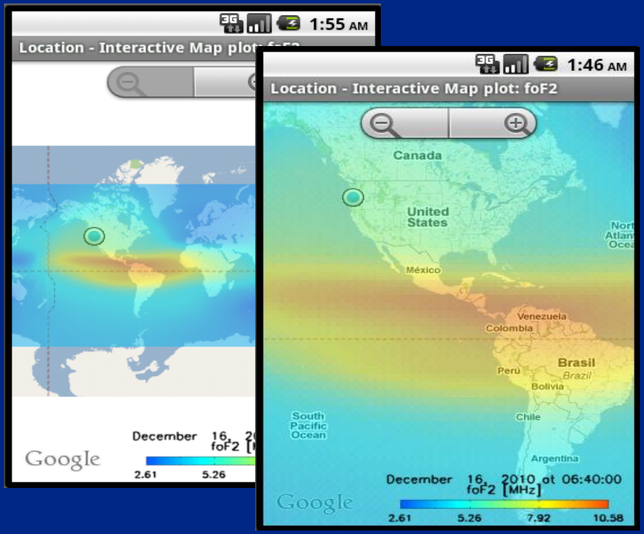
❖Science
❖ Technology
❖ Applications
Bringing It All Together

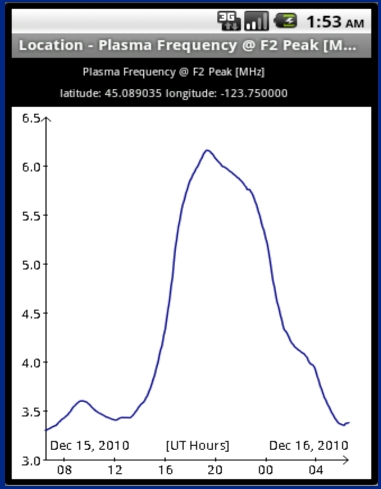
Spaceweather Modeling	Data Assimilation	Data Analysis	Instrument Development	Space Systems
TIMEGCM	AMIE High-latitude Electrodynamics	Space Based Data	HF TID Mapper	NSF DICE CubeSat
	IDA4D Global Ionosphere	Ground Based Data	GPS-based Space Weather Monitor	SMC SENSE
			Fabry-Perot Interferometer	Plug-N-Play Avionics
			Space weather Phone Apps	Scanning Photometer System
				Space-based GPS receiver
				Temperature Sensor (Balloon) & Dosimeter

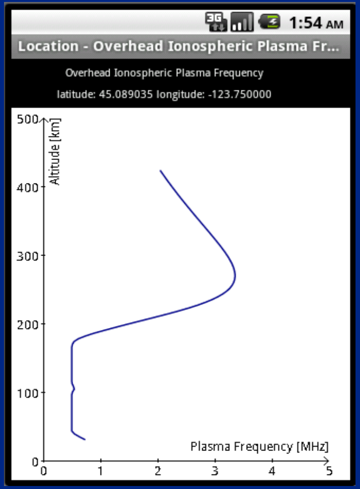
Space Weather and SSA

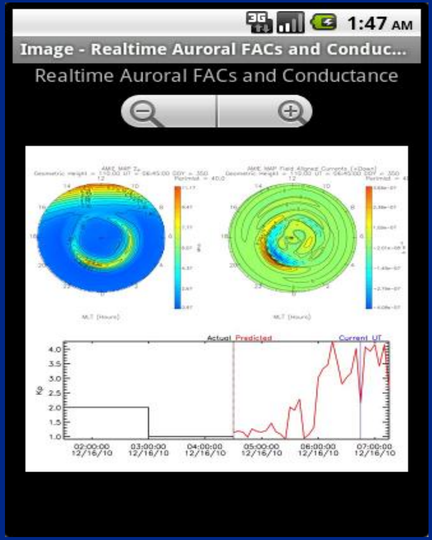
REALTIME SPACE-WEATHER:

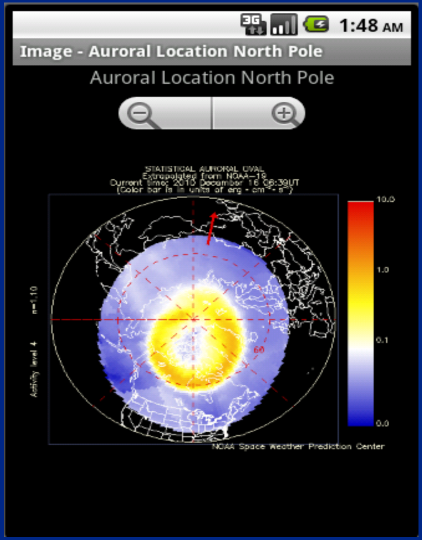
ASTRA Space Weather App

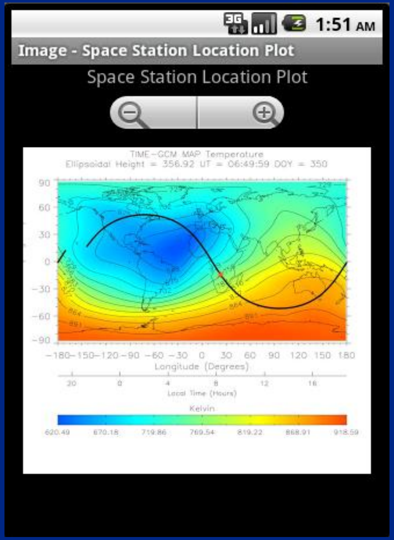












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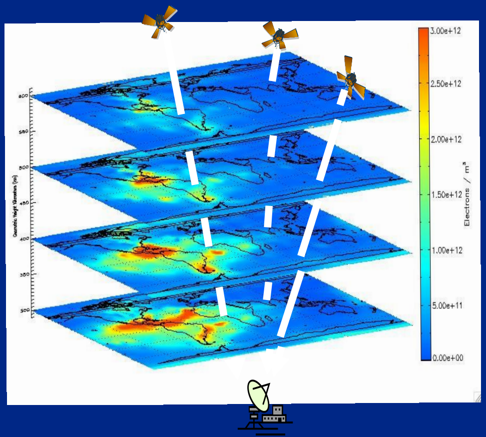
Space Weather and SSA

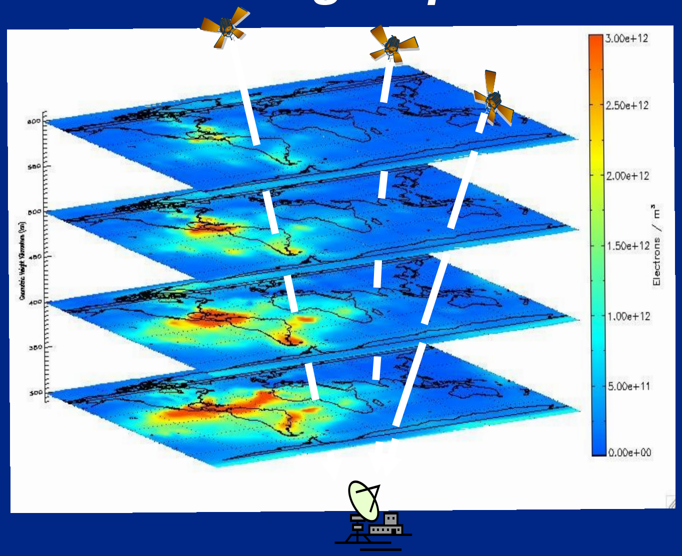
Outline

- **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

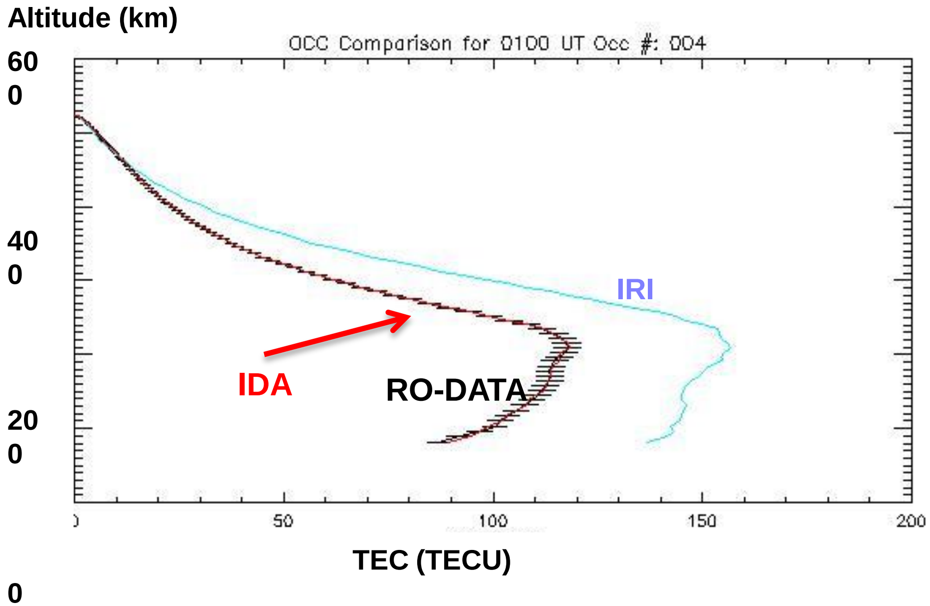


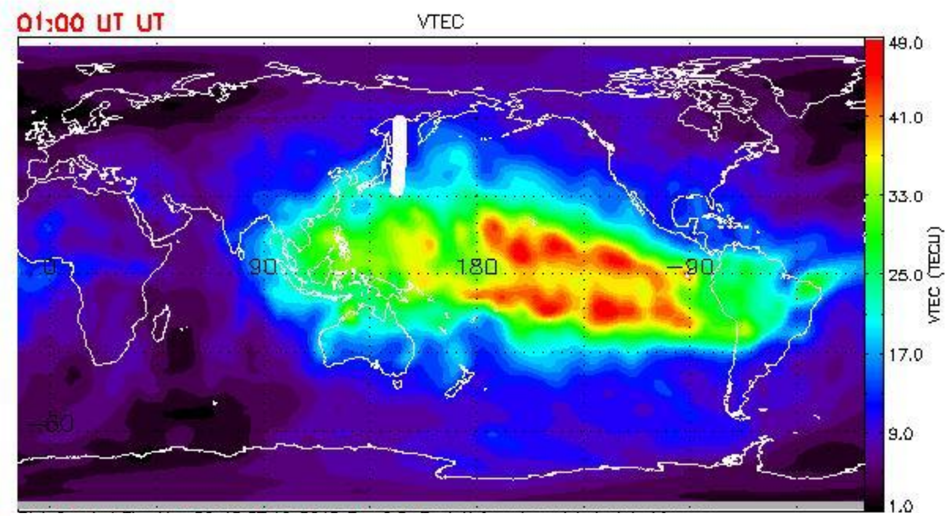
- Configuration files
  - *User configurable error covariance*
  - model of background ionosphere
  - Amount of and type of data
  - Regional/global
  - Time steps
  - Convergence criteria
  - Data sampling rates, averaging windows, sampling windows, data representation errors

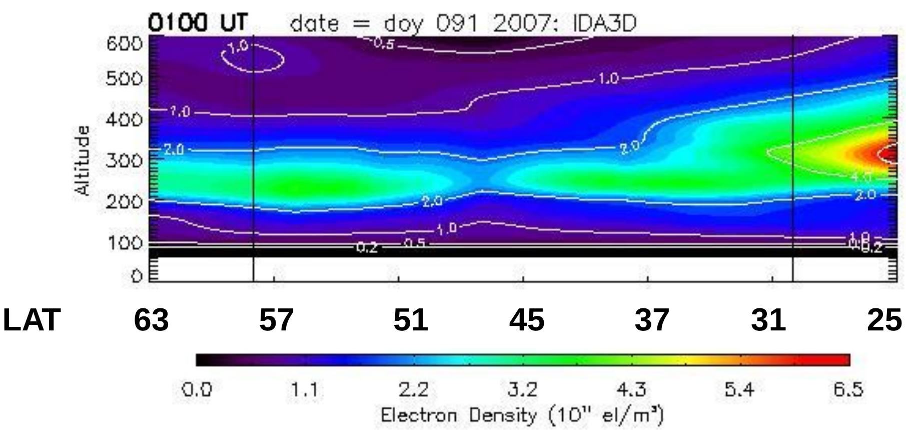
IDA4D and Radio Occultations

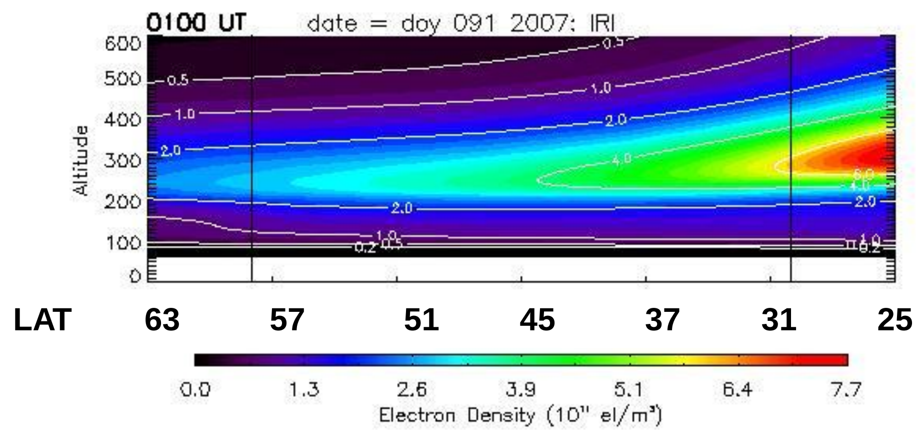
- IDA4D has routinely ingested slant TEC from Radio Occultations since 2002.
  - Slant TEC between LEO receiver and GPS transmitter
  - *not Abel inverted Ne profiles*
- IDA4D has ingested RO TEC from:
  - PICOSat, IOX, CHAMP, SAC-C, GRACE and COSMIC
- Typical case with CHAMP, GRACE and 6 COSMIC: April 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









E-region Densities from RO

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**:

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

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

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

Unfortunately (or fortunately for some of us), **n_e(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.

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$$TEC(h_t) = 2\int_{h_t}^{150} \frac{n_e(r)rdr}{\sqrt{r^2 - h_t^2}} + \int_{s_1^{150}}^{\infty} n_e(s_1)ds_1 + \int_{s_2^{150}}^{\infty} n_e(s_2)ds_2$$

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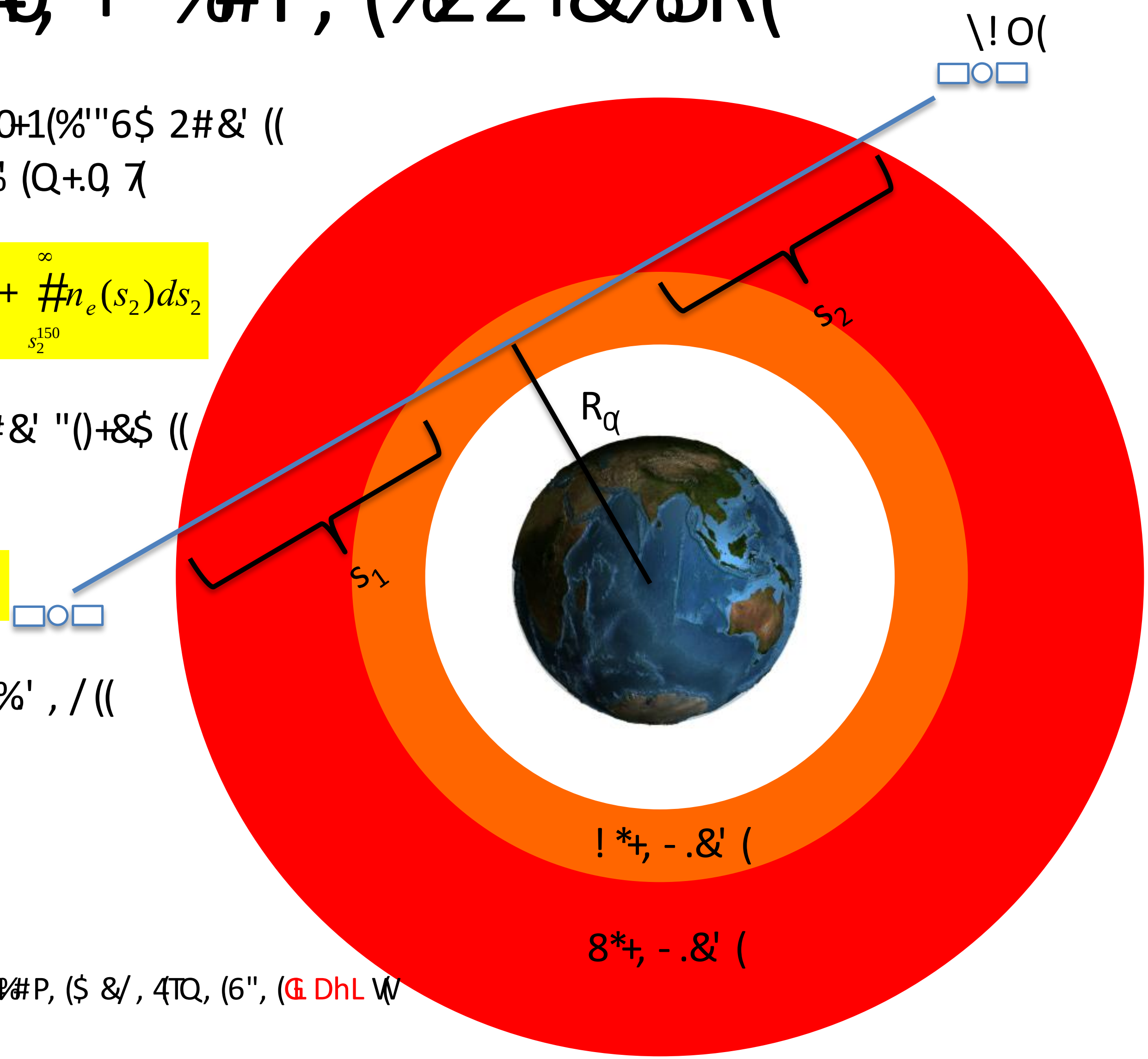

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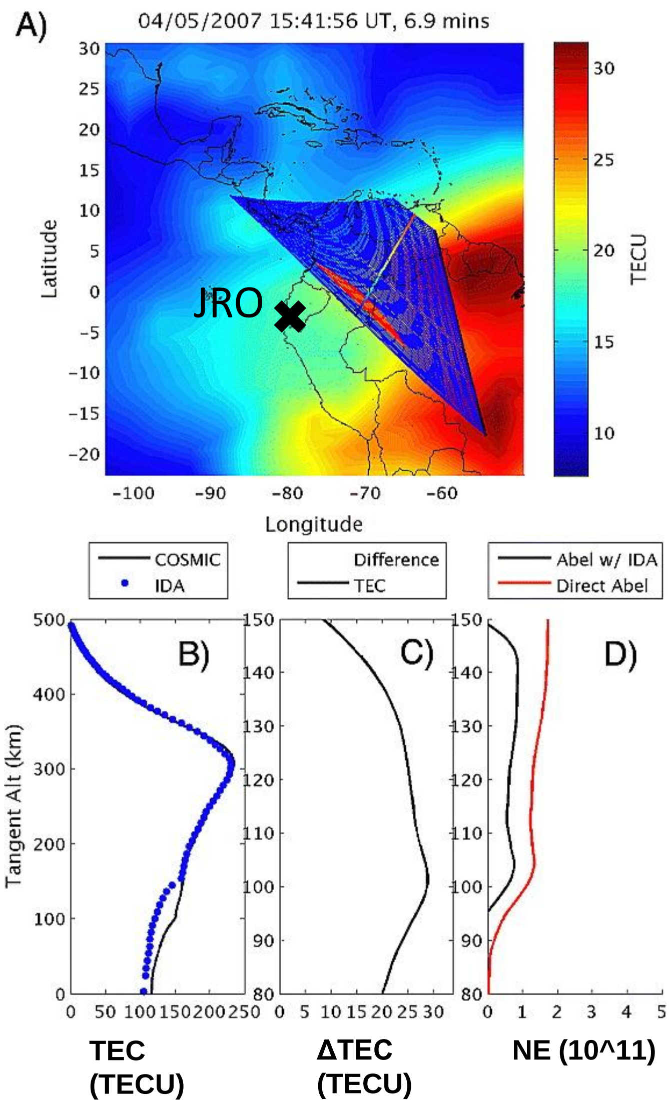
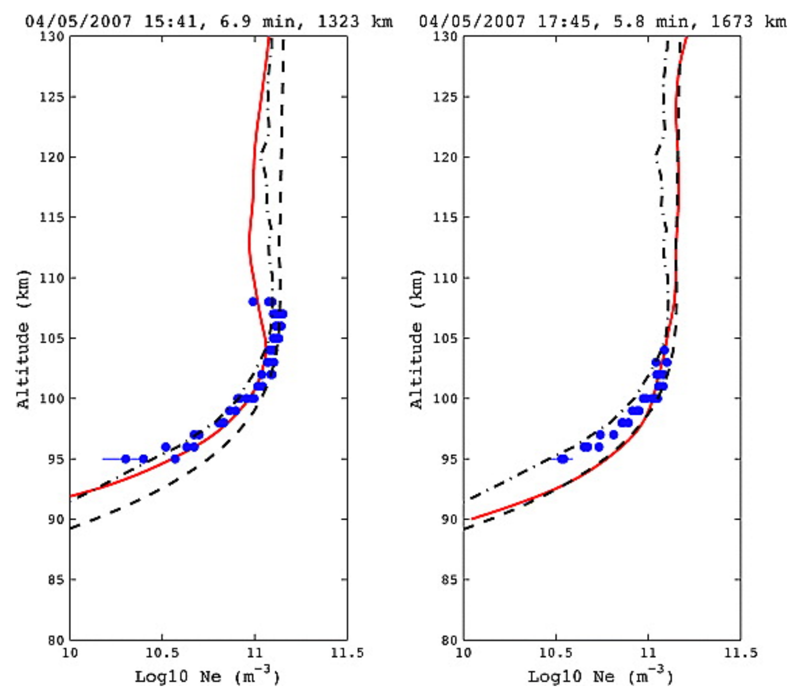
Validation versus Radar Measurements



Validation/Comparison Analysis



Nicolls et al. (2009)

Jicamarca-Paracas Bistatic Radar

- Inversion

-.- FIRI

-- IRI

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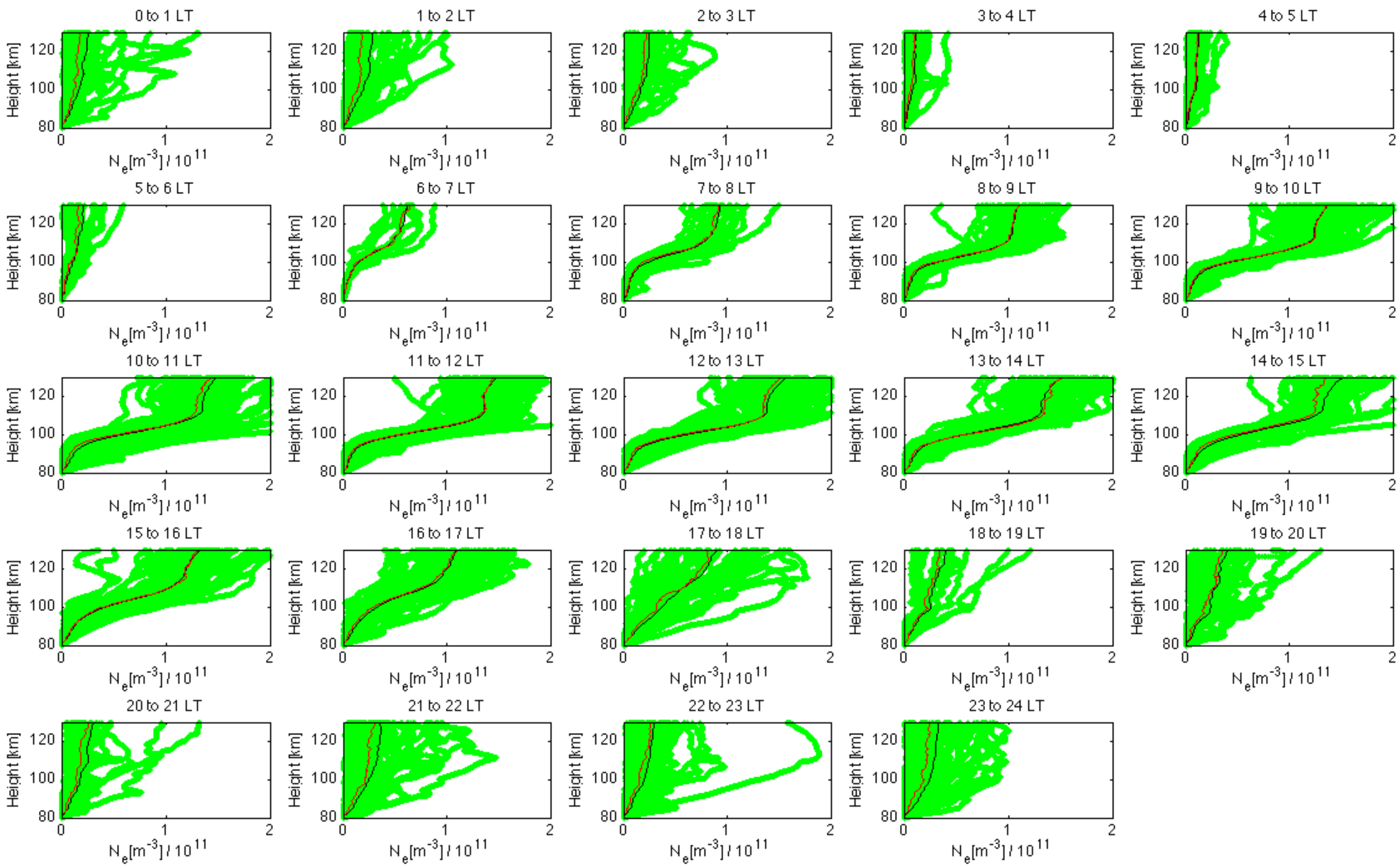

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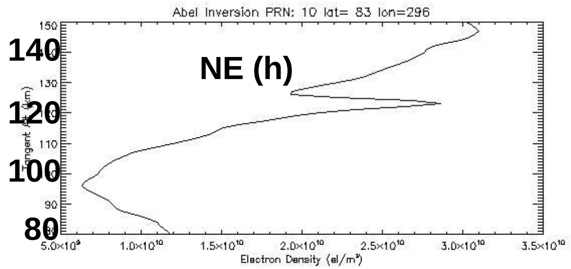
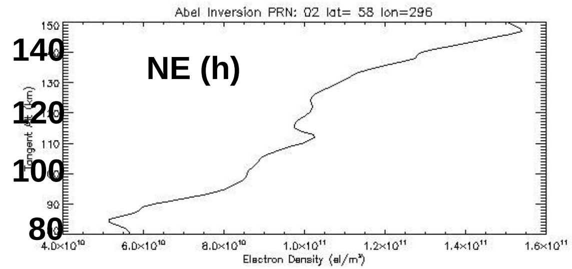
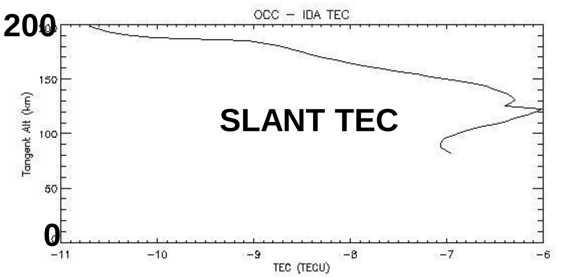
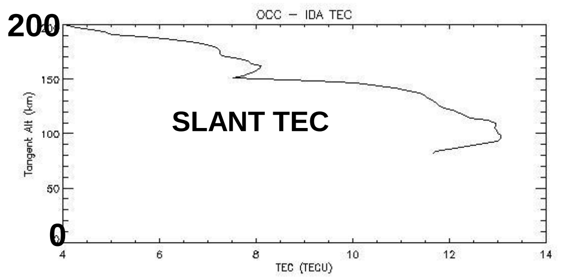
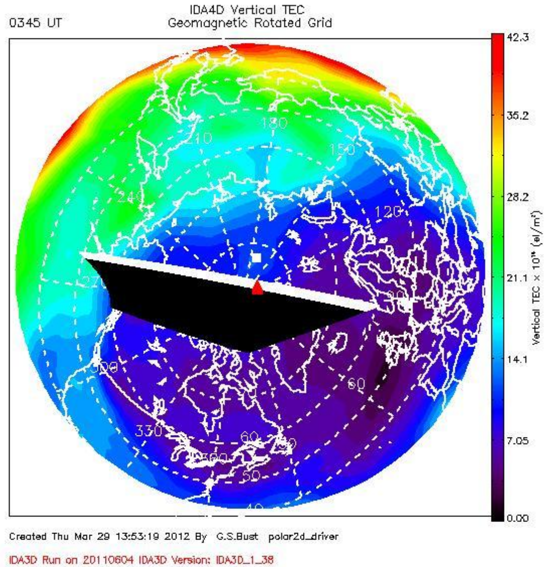
Polar E-region Densities and Conductances

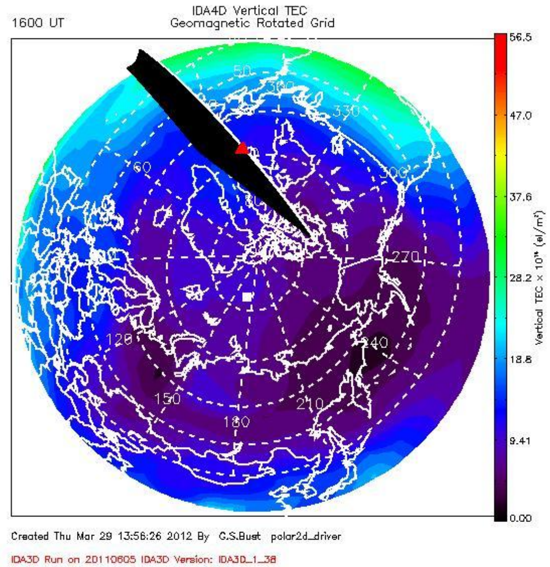


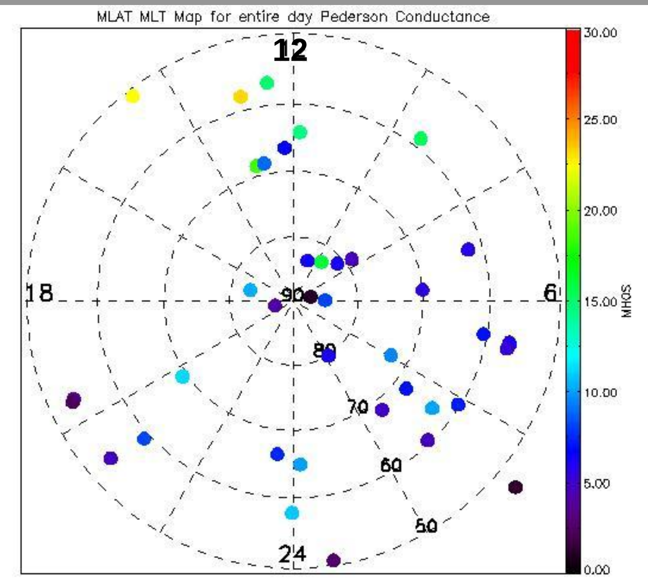


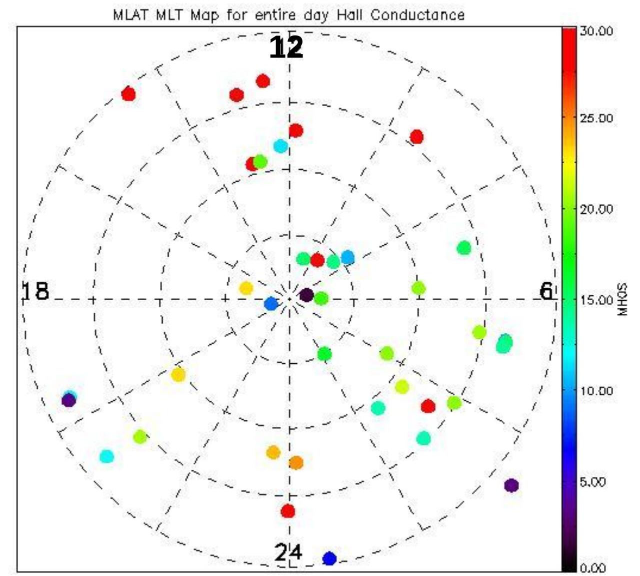










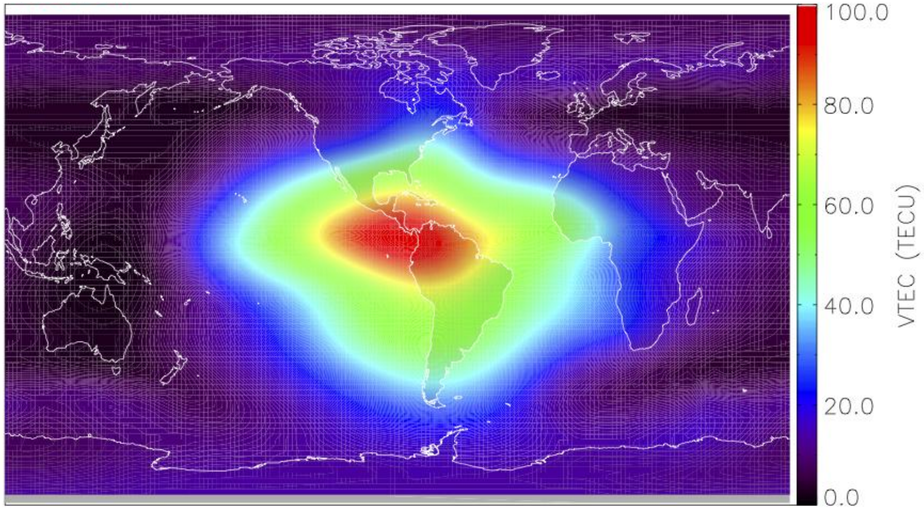


GEOScan: Simulating 66 LEO satellites with RO

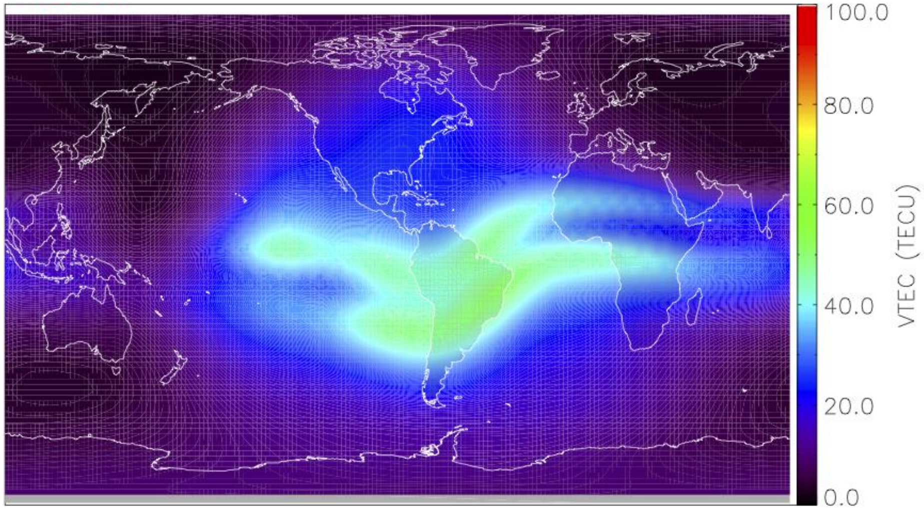
- 66 Iridium Satellites in Polar orbit at ~ 780 km altitude
- Simulate RO TEC data for 3 hours
  - November 20, 2003 Superstorm 15-18 UT
  - Use TIMEGCM simulation as "Ground Truth"
  - Fly all 66 satellites in actual Iridium orbital planes with correct geometry
  - Use actual GPS ephemeris for the day 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

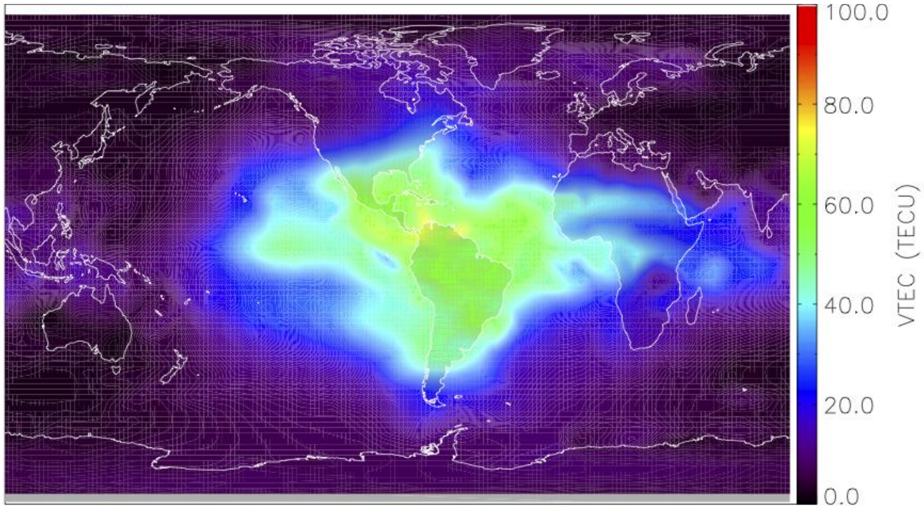
TRUTH



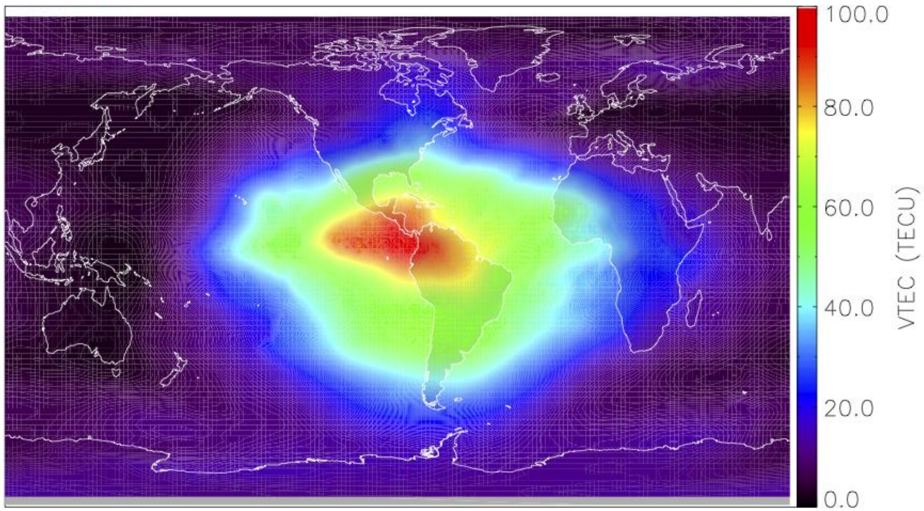
IRI



Ground-based GPS TEC



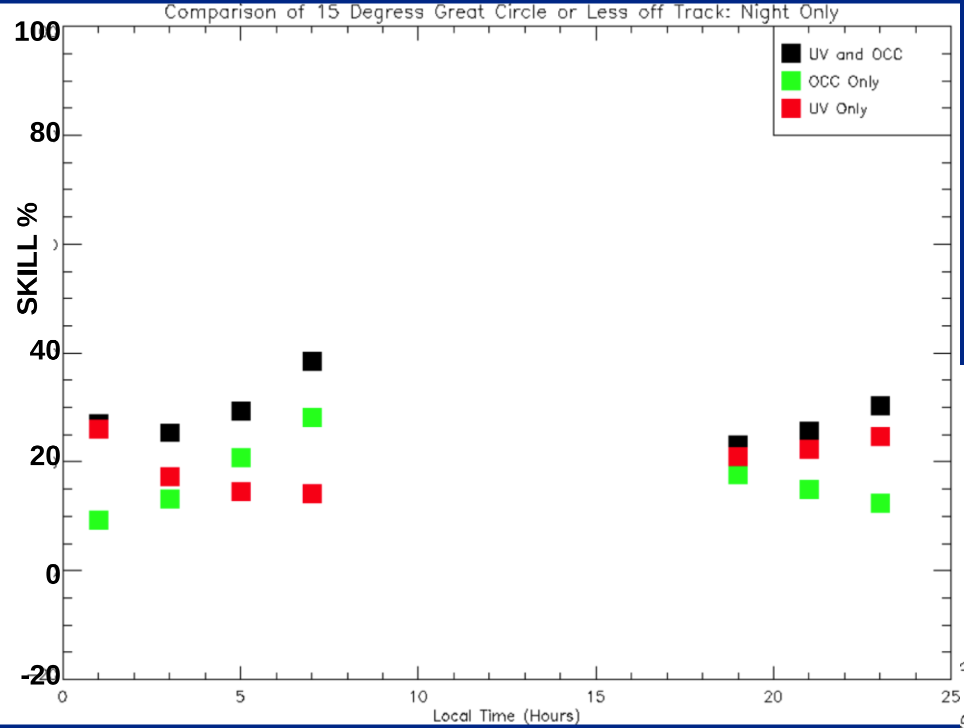
IDA4D

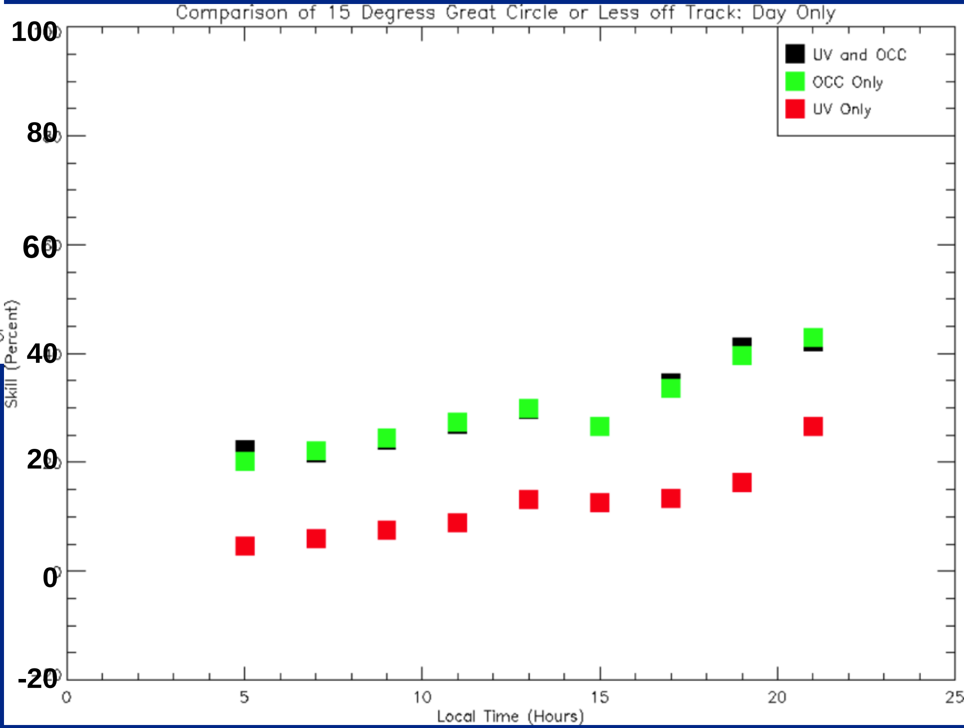


CubeSat Mission Simulations

- 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





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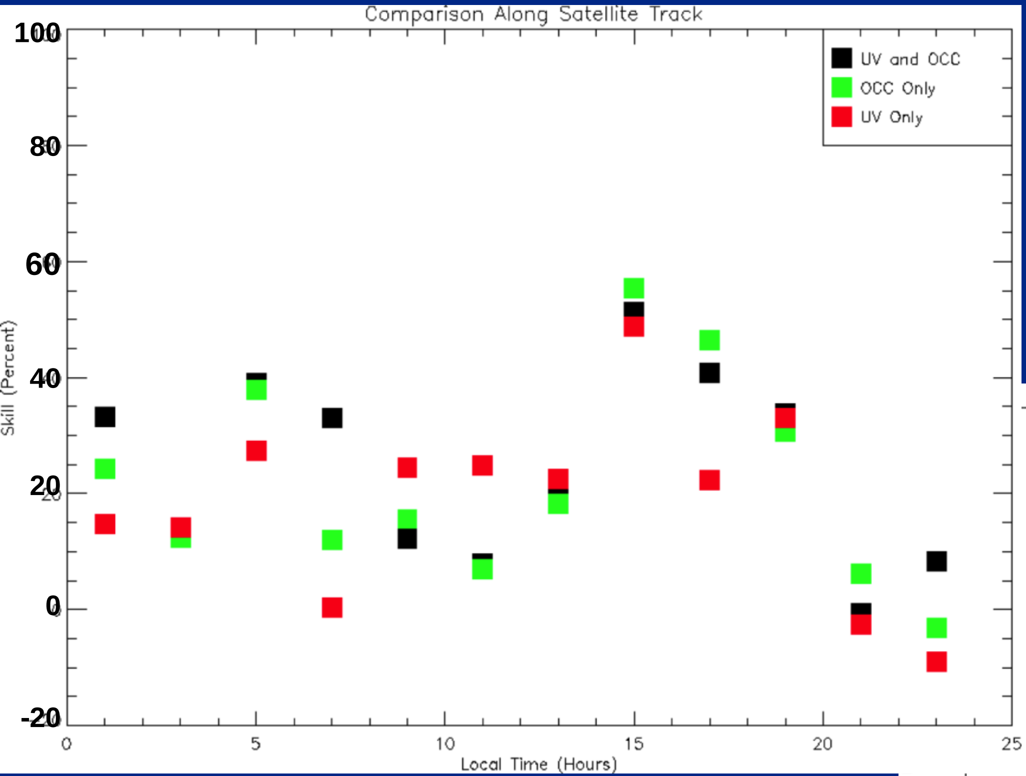

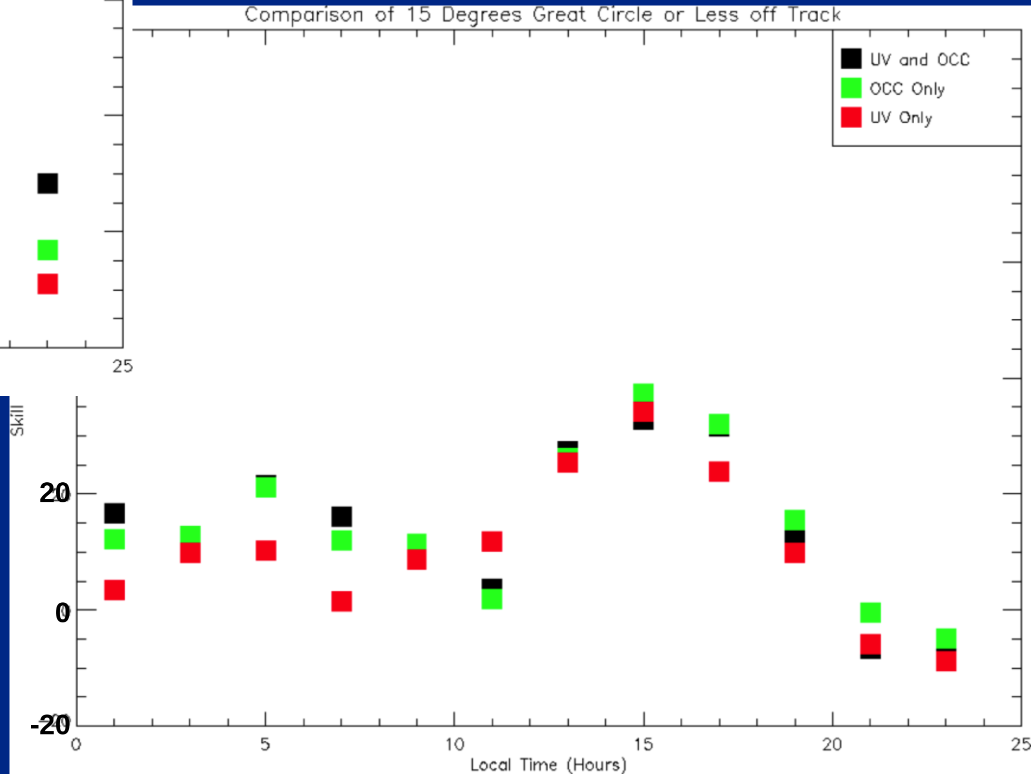

Summary

- 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, varyng number of satellites

  - Seems capable of retrievig enture ionos, including horiz struc.
- Other simulations for Cubesats have shown the performance improvements obtained by RO.

Derivation of Skill Score Metric

D_i - IDA4D data point value

M_i - Baseline data point value

T_i, ν_i^T - Truth data point value, Truth variance

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

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

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