Radio Occultation Effective Coverage/Refresh Analysis for Mid- & Low-Latitude Total Electron Content Specification

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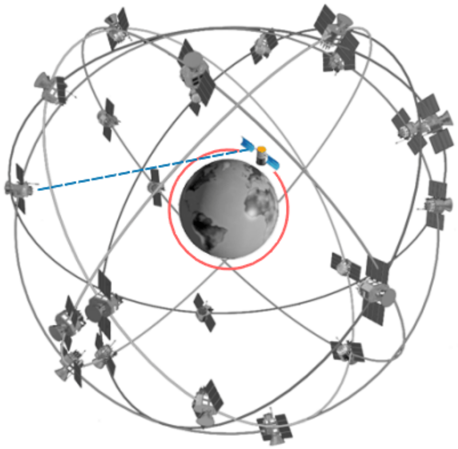
Coverage/Refresh for Radio Occultation (RO)

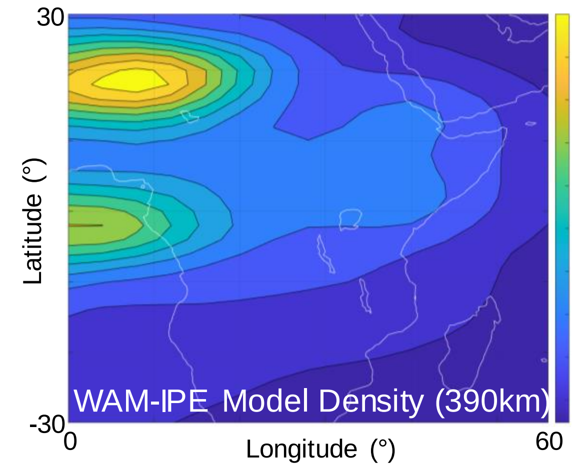
- Coverage & Refresh are key metrics for space-based remote sensing systems
- For sensors that can be conceptualized as having an effective "swath" that "paints the Earth" with observations, this is very intuitive
  - *A point on the Earth is "covered" when it is within the sensor swath*
  - *The refresh time for a point on the Earth is the time between observations*
  - *When sensor/observation architecture coverage/refresh requirements are met (with appropriate accuracy) the system meets its sensing objectives*
- However, RO observations are a time series of collections along lines-of-sight between dynamically moving LEO and GNSS satellites: not at all "swath-like"
  - *RO systems are typically characterized by the number of occultations they provide as opposed to whether they meet coverage/refresh requirements*
- Applying Coverage/Refresh metrics to RO systems is equivalent to answering the question, "How many occultations are needed & where do they need to be?"
  - *To answer this question, we must understand how the RO data is used to address particular applications of interest*
- This presentation describes an ongoing investigation into RO Coverage/Refresh assessment for ionospheric total electron content (TEC) specification



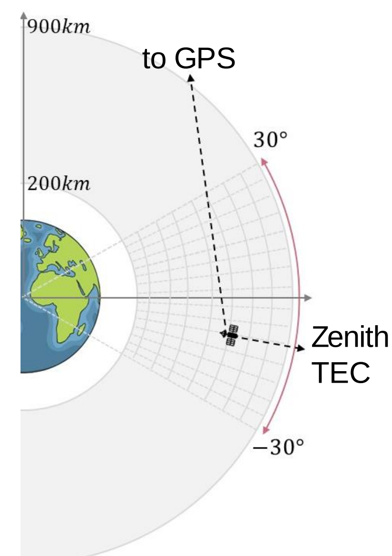
Modeling Approach & Simplifying Assumptions

Truth model: WAM-IPE ↓

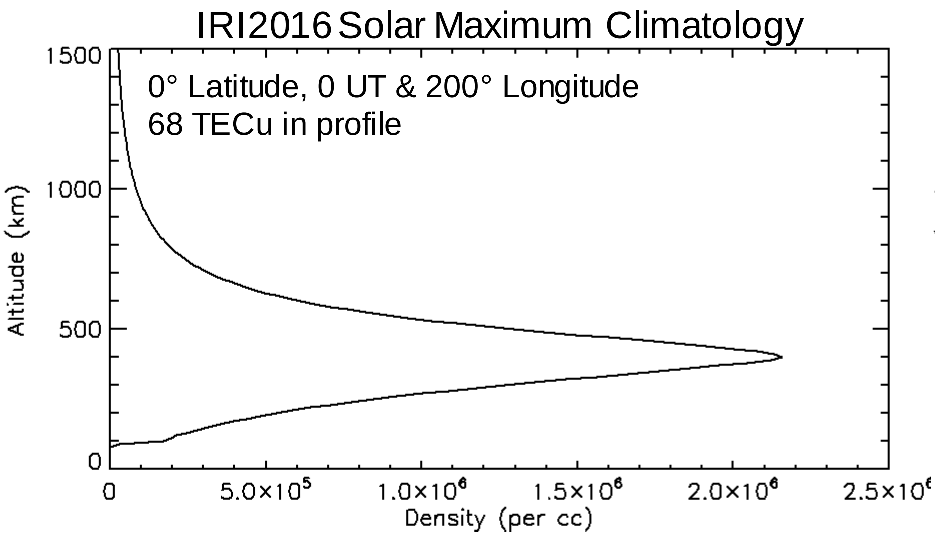
GNSS/LEO RO Orbital Simulation → RO Lines of Sight Selection → Absolute TEC Generation → Ionospheric Inversion → Solution Evaluation

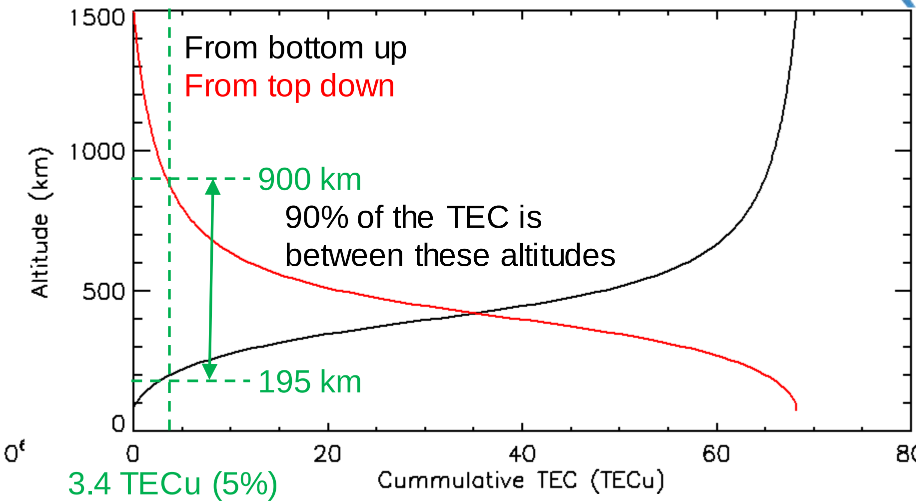


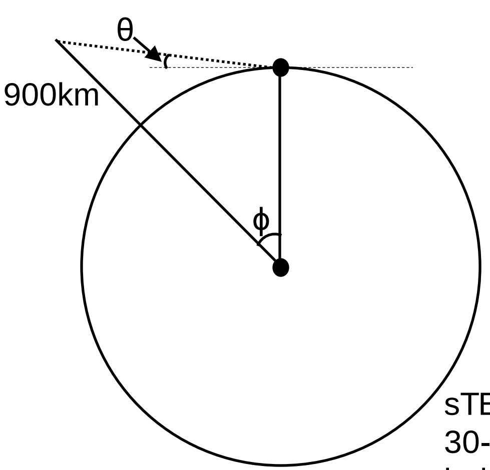
- Meso-scale analysis: looking at ability to retrieve medium to large scale ionospheric features
- Avoid highly structured regions: auroral zone & low latitude turbulence
- Initial ionospheric retrieval is regional, not global
  - *Region of Interest (ROI): ±30° lat/0-60° lon/200-900km alt*
  - *Grid spacing: 2° lat × 4° lon × 47km alt (30×15×15 voxels)*
- Temporal stationarity assumed: 60 minutes of RO data drives ionospheric inversion
- Initial focus is on occultation TEC
  - *Zenith hemisphere TEC is not yet realistically modeled*
  - *Overhead arcs from LEO satellites embedded in ROI replaced by zenith-viewing lines of sight*



Region of Interest (ROI) Determination

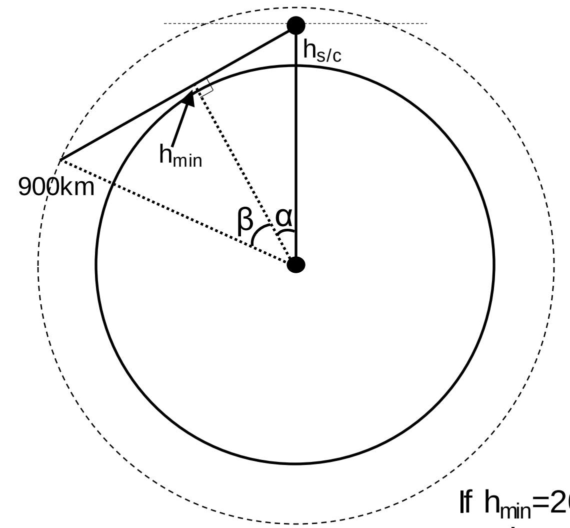






θ	ϕ
0°	28.8°
10°	20.4°
20°	14.5°

sTEC evaluation requires 30-60° around each point being evaluated



$h_{s/c}$	α
500 km	17.0°
600 km	19.5°
700 km	21.7°
800 km	23.6°

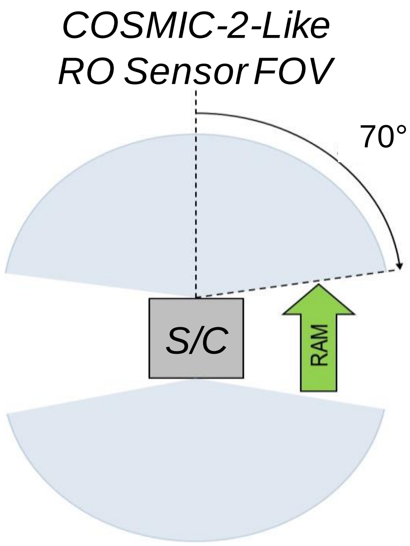
If h_{min}=200 km, then β= 25.3°, so total Earth-angle range covered by RO is 42-49° depending on $h_{s/c}$

Ideal ROI: 200-900km altitude, ±15° ± 45° lat/lon

Initial analysis compromise: ±30° lat/lon instead of ±60°

LEO/GNSS Satellite Constellations & RO Capability

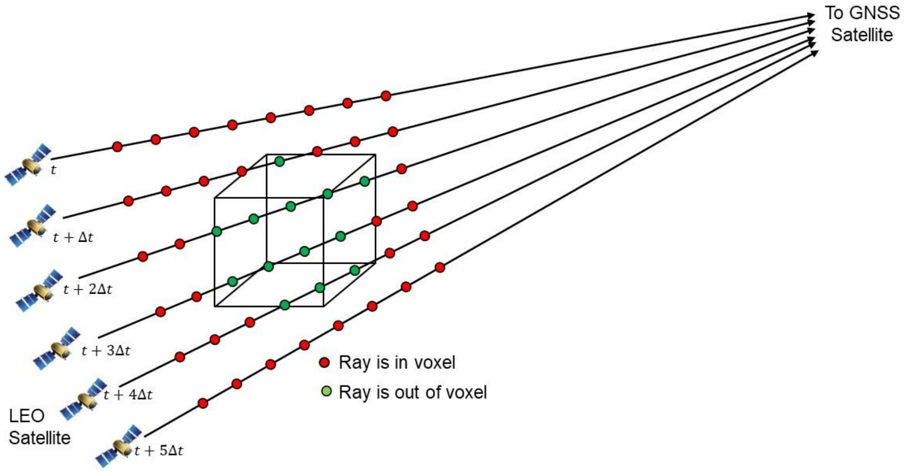
- LEO constellation
  - *3 shells with 1024 satellites each*
  - *Each shell is a Walker constellation consisting of 32 planes of 32 satellites each*
  - *5.6° mean anomaly shift between adjacent planes to achieve optimal satellite spacing*
  - *Shell altitudes: 550, 650, 720 km*
  - *Shell inclinations: 24°, 48°, 72°*
- GNSS constellation
  - *30 GPS*
  - *23 GLONASS*
  - *21 Galileo*
  - *44 Beidou*
- RO sensor capabilities
  - *COSMIC-2-like antenna configuration assumed to enable tracking of all occultations within ±70° azimuth relative to velocity/anti-velocity vectors*
  - *Able to track either only GPS or all 4 GNSS satellites*

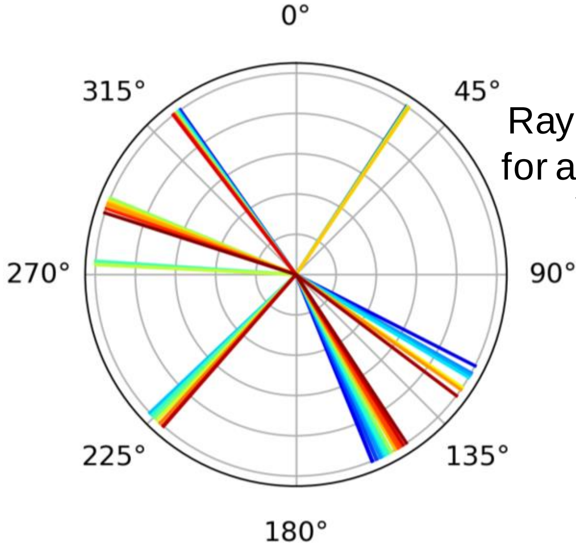


Selection of RO Data to Feed the Inversion

"Unique Rays" Analysis

- 5s simulation timestep produces >1.7M rays over a 1-hour simulation (3,072 LEO satellites/GPS-only case), but many of these rays are redundant for the purposes of an ionospheric inversion
- We developed a "unique rays" analysis to select a reasonable subset of the simulated rays along which absolute TEC is calculated to drive the inversion
- ROI voxels are evaluated in sequence: rays passing through each voxel are assessed for "uniqueness" and any "unique rays" are added to the "unique rays" list
- To be considered "unique", rays must pass both temporal & orientation criteria
  - *Temporal: A specific voxel is considered to be "touched" only once by a sequence of consecutive rays passing through it*
  - *Orientation: The azimuth relative to north of the ray must differ from all previously identified unique rays by > 10° (ad hoc value)*



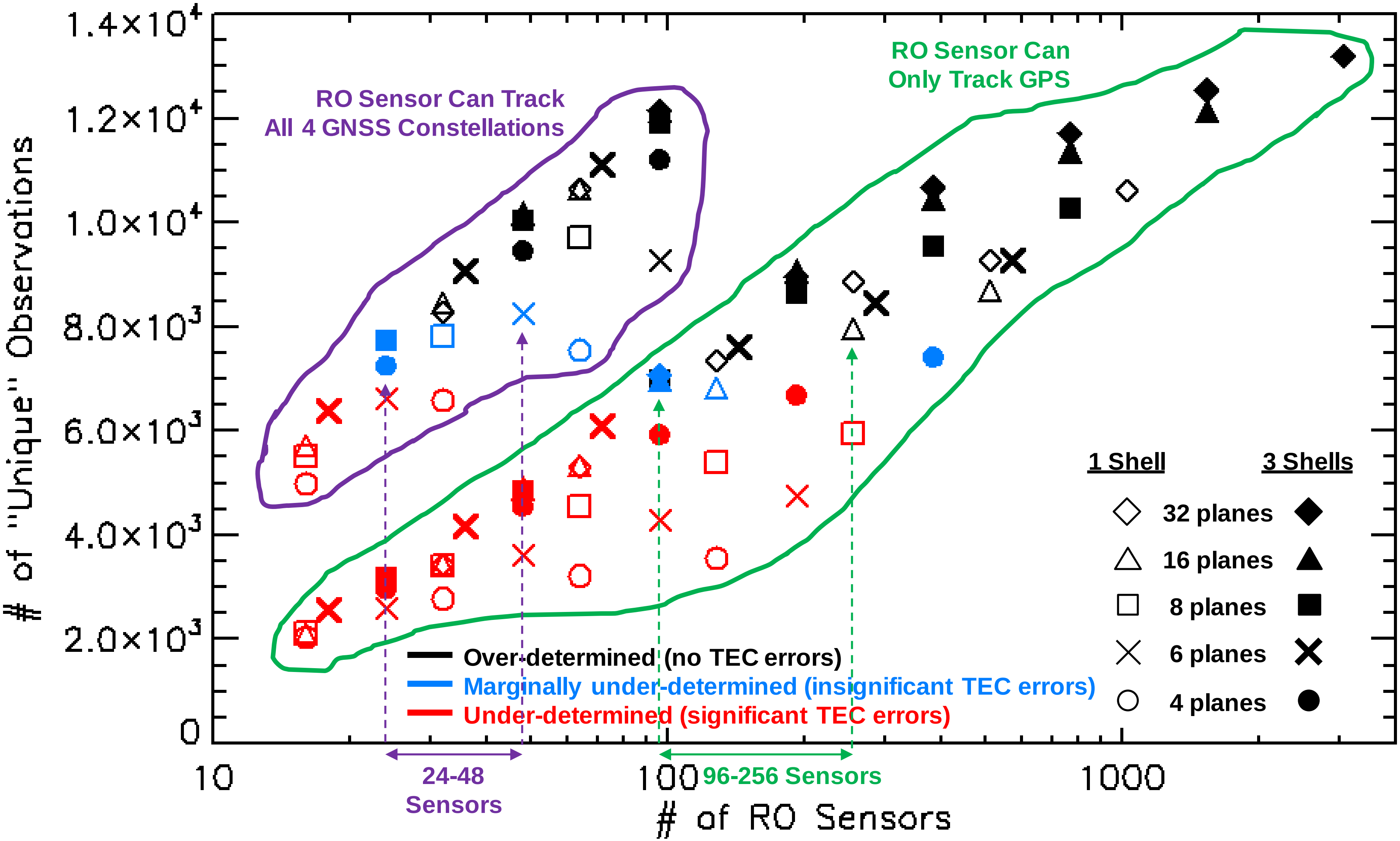


Ray Azimuths for a Particular Voxel

RO Constellation Performance Analysis

- Starting from the 3,072 satellite baseline, the # of satellites is reduced
  - *Vary the number of shells (3 or 1), orbit planes (32, 16, 8, 6, 4) & satellites/plane (1-32)*
    - 1-shell cases use just the "middle" inclination satellites: 48°/650km
  - *In each configuration, Walker f-parameters are adjusted to achieve a spatially/temporally uniform distribution of satellites (qualitative assessment)*
- For each configuration determine "unique" rays & assess ionospheric inversion performance
  - *Is the inversion full rank (over-determined) => perfect solution*
  - *If not, is it near full rank (marginally under-determined) => ground-based sTEC errors are insignificant*
  - *If not, the inversion is under-determined => significant sTEC specification errors*
- Impact of including RO sensor noise was assessed for a subset of the orbital configurations
  - *Tests solution stability*
  - *Full rank and marginally under-determined cases are generally not significantly impacted by noise*

Constellation Analysis Results



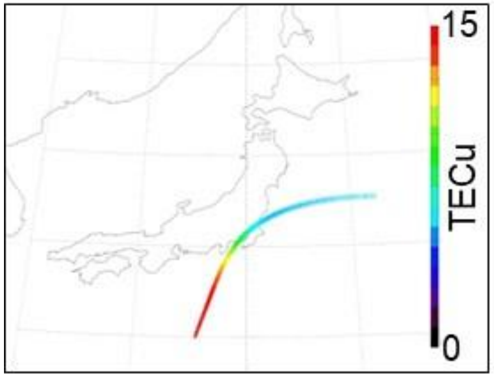
RO Sensor Capability Is The Most Significant Performance Driver

What Real-World TEC Accuracy Can Be Achieved?

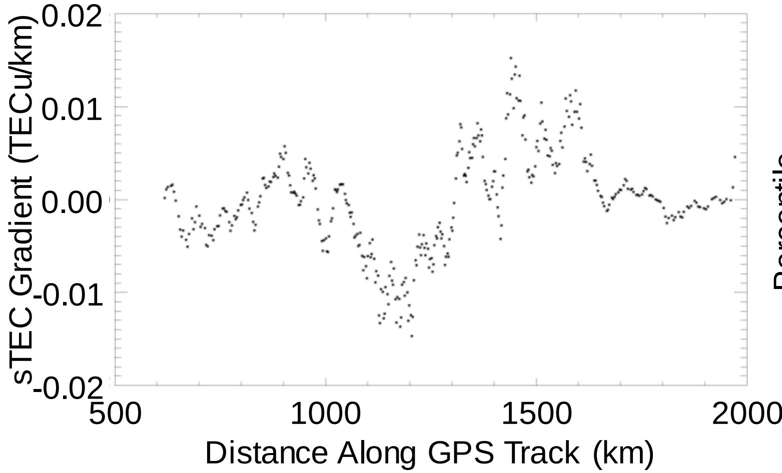
- For our simulation, with sufficient RO sensors appropriately distributed, it is possible to accurately retrieve the “true” ionosphere
  - *Although WAM-IPE was used as truth in this analysis, any ionospheric truth would do as well because the inversion process is over-determined & exact*
- The ability to accurately recover real-world TEC is connected to the assumptions made by the truth model: specifically, those assumptions implied by the model’s horizontal cell size
  - *To the degree that the model cell size (2°×4°) supports resolution of features of interest, the real-world retrievals will also be accurate*
  - *Sharp horizontal gradients that result in significant TEC changes over scale sizes smaller than or similar to the model grid size cannot be resolved and will result in TEC specification errors (e.g., low latitude “bubbles”/turbulence currently excluded from this analysis)*

Slant-Path TEC (sTEC) Gradient Study: A Quiet Day

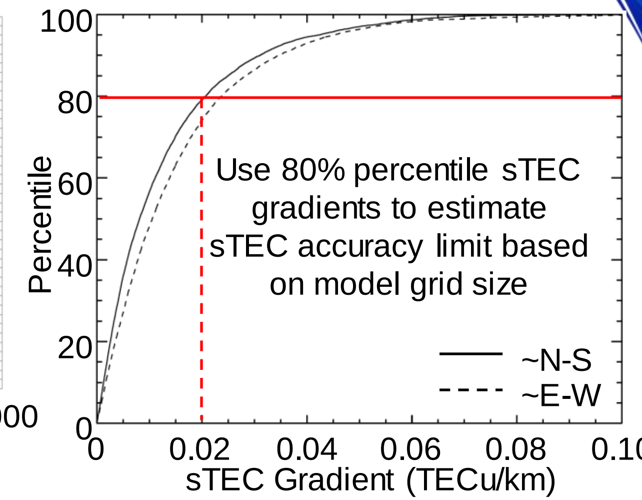
Mid-Latitude Ground Station sTEC Along a GPS Track



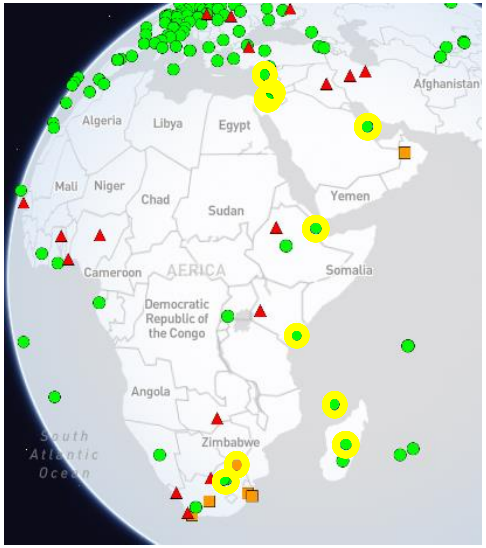
sTEC Gradients Along a GPS Track

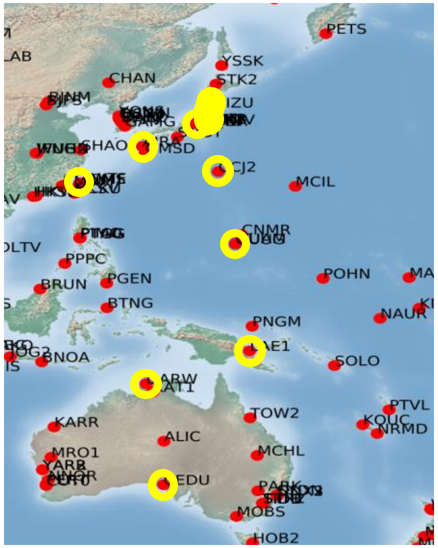


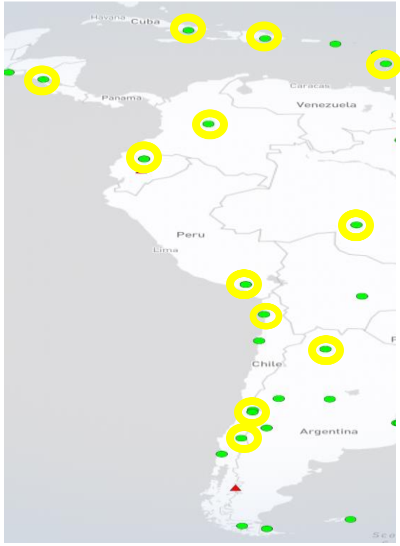
Cumulative sTEC Gradient Distribution



3 Longitude Sectors Evaluated



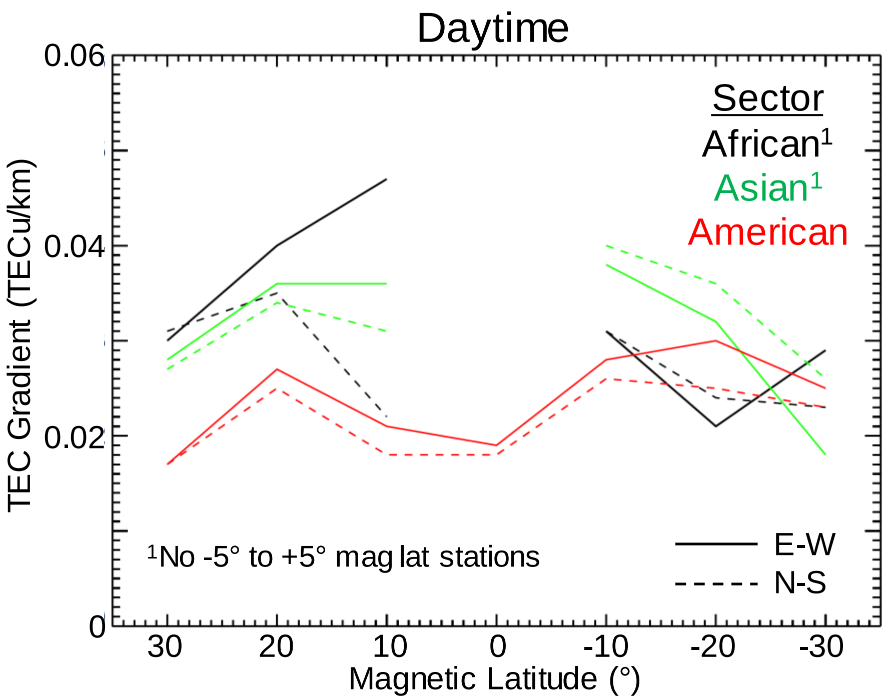


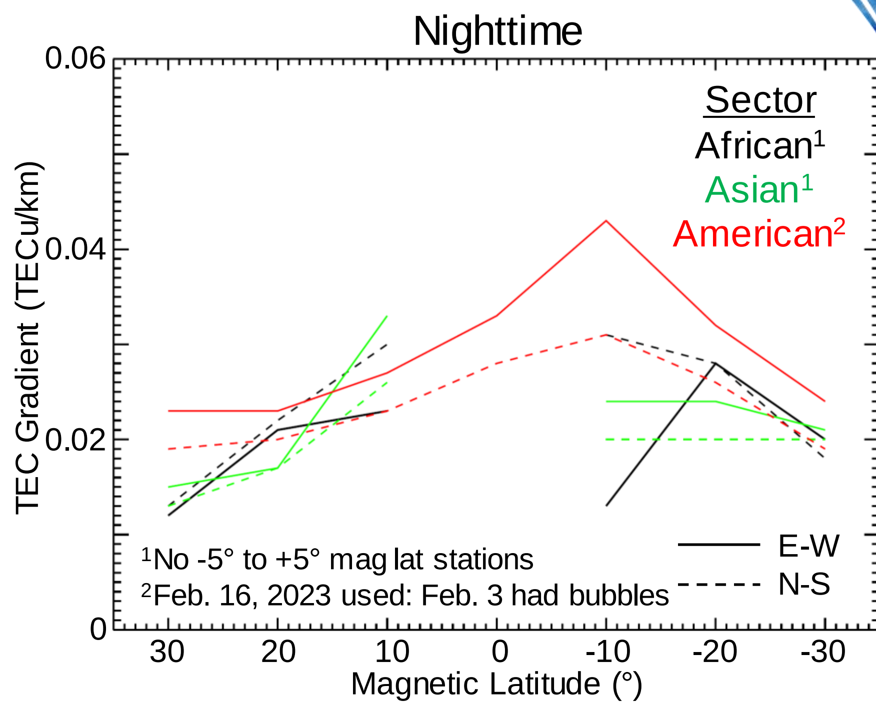


Yellow circles denote ground GPS stations used in study

80th Percentile TEC Gradients in 3 Longitude Sectors

Quiet day (February 3, 2023[2]) averages over 10° magnetic latitude bins





- Daytime gradients range from 0.018 to 0.047 E-W & 0.018 to 0.040 N-S (TECu/km)
- Nighttime gradients range from 0.012 to 0.043 E-W & 0.013 to 0.030 N-S (TECu/km)
- Analysis indicates that, for the 2°×4° horizontal grid size, these gradients result in 1-5 TECu specification errors
  - *E-W errors are larger than N-S due to the larger E-W grid spacing*
  - *1-5 TECu is the minimum error due to finite cell size considerations: realistic assimilative models may have additional errors*

Summary & Future Analysis Plans

- **<u>If</u>** the ionosphere could be accurately characterized by a 2°×4°×47km (lat×lon×alt) grid,
- **<u>and if</u>** the study assumptions (e.g., 60-min stationarity, regional analysis, etc.) do not represent substantial differences relative to real-world assimilative models,
- **<u>then</u>** ~36 uniformly distributed RO sensors capable of tracking the 4 major GNSS constellations would provide sufficient data for sTEC specification at ~1-5 TECu accuracy under geomagnetically quiet conditions

- Open issues with current ionospheric solver:
  - *Poor vertical resolution is an error source*
  - *Absolute sTEC ingest approach is inconsistent with proper modeling of sensor noise impacts*
  - *Overhead ray paths are non-physical*
  - *Solver is regional in nature, not global*
- Future Plans to Refine the Analysis
  - *Increase vertical resolution and/or replace current vertical grid with empirical orthonormal functions*
  - *Replace absolute sTEC data ingest with relative sTEC and reassess sensor noise impacts*
  - *Incorporate geometrically realistic zenith hemisphere RO sTEC observations*
  - *Expand regional grid towards a more global representation*
  - *Evaluate ionospheric gradients using ground-based data during geomagnetically active days to determine sTEC accuracy limits under disturbed conditions*
  - *Decrease horizontal grid spacing to explore limits of RO ability to improve accuracy at smaller scale sizes*