This is a summary of developments for GPS TEC (Total Electron Content) measurements, spanning over 15 years, and leading to ground-based measurements of the plasmasphere. The ionosphere/plasmasphere depiction is derived from SUPIM (Sheffield University Plasmasphere Ionosphere Model) for a saturated plasmasphere during low solar flux. The plasmapause is at $L=3.77$.

The inner red ring designates the ionosphere/plasmasphere boundary (at 1000 km altitude); the outer red ring designates the GPS altitude; the gray rings are at radii 10000 km, 15000 km, 20000 km, and 25000 km. The sun (yellow icon) is at the right, to designate the daytime side and equinox condition.

Lowest densities occur within the night-time ionosphere.

Note: Supplements to the original presentation appear on slides with “a”, “b”, “c”, or “d” slide number suffixes.
Overview

• Background for SCORE and SCORPION
• SCORE Results
• Encountering the Plasmasphere
• The First SCORPION of All
• SCORPION - The Next Generation
• SCORPION - IBSS 2007 Results
• Here and the Plasmasphere
• There and Everywhere
• Evaluating the Calibrations (and TEC)

SCORPION - The Next Generation: Developments after Ascension Island
SCORPION - IBSS 2007 results: Validations against SUPIM; Corroborations against other data
Here and the Plasmasphere: Local plasmasphere effects for New England and contiguous US
There and Everywhere: Consideration for Equatorial/Low-latitude regions, notably the Plasmasphere Electron Content (PEC) baseline
Evaluating the Calibrations: Consistencies between stations and with other data sources
Background for SCORE and SCORPION

- Both methods are intended to perform calibrations for individual GPS receivers, by coordinating raw TEC measurements (with satellite and receiver biases).
- Conjunctions between GPS satellites are defined in latitude ($\lambda$) and local time ($\tau$) coordinates for the Ionosphere Penetration Point (IPP). (This presumes a stationary ionosphere in Earth-centered solar coordinates, extending Leitinger et al. (1975).)
- Equivalent vertical TEC (V) for the two satellites are presumed equal at a conjunction, so $V_1(\phi_1, \varepsilon_1, t_1) = V_2(\phi_2, \varepsilon_2, t_2)$, where $(\phi_1, \varepsilon_1, t_1)$ and $(\phi_2, \varepsilon_2, t_2)$ are azimuths, elevations, and Universal Times for the two measurements.

From Mazzella et al., 2001
Background for SCORE and SCORPION

• For more conjunctions than satellites (and associated biases), a Least Squares formulation is employed:

- Minimize $E = \sum w_{ij} \sum w_{i\beta} \sum w_{\alpha\beta} [V_{\alpha}(\phi_{i\alpha}, \epsilon_{i\alpha}, t_{i\alpha}) - V_{\beta}(\phi_{\beta\beta}, \epsilon_{\beta\beta}, t_{\beta\beta})]^2$

where $W_{\alpha\beta}$ is a weight factor defining the conjunction region:

$W_{\alpha\beta} = \exp(-[\lambda_{i\alpha} - \lambda_{\beta\beta}]^{2})\exp(-[\tau_{i\alpha} - \tau_{\beta\beta}]^{2})$

for scaling values $\Delta \lambda$ and $\Delta \tau$.

• This was later expanded to

$W_{\alpha\beta} = \exp(-[\lambda_{i\alpha} - \lambda_{\beta\beta}]^{2})\exp(-[\tau_{i\alpha} - \tau_{\beta\beta}]^{2})\exp(-[t_{i\alpha} - t_{\beta\beta}]^{2})\sin(\epsilon_{i\alpha})^i\sin(\epsilon_{\beta\beta})^i$

to impose limits on Universal Time differences and accommodate inaccuracies in the conversion from slant TEC to equivalent vertical TEC. [Mazzella et al., 2002]

alpha, beta are satellite indices
i, j are data sample indices for individual satellites
Strict limits on latitude, local time, and Universal Time differences are also implemented
Background for SCORE and SCORPION

For SCORE:
\[ V_i(\phi, \varepsilon, t) = f(\varepsilon) \times [M_i(\phi, \varepsilon, t) - (B_s + B_r)] \]

where \( M_i(\phi, \varepsilon, t) \) is the measured slant TEC (with biases), \( B_s \) is the satellite bias, \( B_r \) is the receiver bias, and \( f(\varepsilon) \) is the slant-to-vertical conversion factor:
\[ f(\varepsilon) = \cos\{\arcsin(R_e \cdot \cos(\varepsilon)) / (R_e + H_i)\} \]
with \( R_e \) as the Earth's radius and \( H_i \) as the effective ionosphere altitude.

Standard "thin-shell" slant TEC conversion factor, but usually using \( H = 350 \) km
SCORE Results

• Because "E" is a quadratic form in the combined satellite and receiver biases, the biases can readily be determined using the derivative minimization of "E". (The determination of the coefficients from the data was the "slow" step.)
• SCORE was initially developed for the Air Force Ionospheric Measuring System (IMS), but alternative pre-processing can accommodate RINEX data or other formats.
• SCORE was also used for the HAARP (Gakona, Alaska) GPS TEC measurements and displays: www.haarp.alaska.edu/cgi-bin/ashtech/tec.cgi

Only one sample every 2-3 minutes is required for acceptable accuracy
Relative satellite biases can also be incorporated (alternative program implementation for SCORE)
Automated calibrations for HAARP contained provisions for avoiding active ionospheric conditions
Otis Air National Guard Base – First IMS deployment.
Data selected span a one-degree band bracketing the site latitude, for 1995, day 014.
Calibration region spans about 4 degrees in latitude to either direction from site (35-deg elevation threshold).
Initial IMS deployments were for middle/high latitudes (Otis ANGB, MA; Croughton, UK; Thule, Greenland; Shemya, AK), with little plasmasphere influence expected.

Research studies by Nick Lunt [Lunt et al., 1999] (University of Wales at Aberystwyth) using simulated data from Sheffield University Plasmasphere-Ionosphere Model (SUPIM, [Bailey and Balan, 1996]) indicated systematic bias errors (~ -2 TEC units).

Data for 1-degree band centered on site latitude. SUPIM reference (solid line) is local vertical TEC at site.

Wrong VTEC curvature for associated bias error.
Encountering the Plasmasphere

Effect was subsequently identified as plasmasphere influence; vanished for ionosphere-only simulation (with very good bias and VTEC agreements, also corroborating slant factor). Model TEC values were calculated only up to 1100 km; ~1 TEC unit lower than previous plot. Two curves are displayed: GPS pass segments and SUPIM local vertical TEC. Derived biases are within 0.2 TEC units of true values.
Encountering the Plasmasphere

- Fifth IMS deployment was designated for Ascension Island (-7° lat; -15° MLat) in 1999.
- From 1998 Ascension Island campaign, plasmasphere effect on SCORE is opposite that at mid-latitudes; biases are overestimated, producing negative night-time VTEC. [Fremouw et al., 1998]
- Situation cannot be resolved as at Aberystwyth (latitude cutoff for calibration).
Encountering the Plasmasphere

From Fremouw et al., 1998

Biases were decreased by 10 TEC units for plot, to avoid negative night-time TEC excursion

1998, day 090; data selected for 35-degree elevation threshold.
Night-time dispersion in VTEC, with negative TEC excursion except for bias adjustment.
The First SCORPION of All

• Based on Aberystwyth SUPIM simulations, SCORE was adapted to remove the plasmasphere TEC contributions before imposing the VTEC equality at conjunctions.

• Thus, \( V_{\alpha}(\phi_{\alpha}, \epsilon_{\alpha}, t_{\alpha}) = f(\epsilon_{\alpha}) \{ M_{\alpha}(\phi_{\alpha}, \epsilon_{\alpha}, t_{\alpha}) - (B_{\alpha} + B) - P_{\alpha}(\phi_{\alpha}, \epsilon_{\alpha}, t_{\alpha}) \} \), where \( P_{\alpha}(\phi_{\alpha}, \epsilon_{\alpha}, t_{\alpha}) \) is the slant TEC attributable to the plasmasphere.

• Based on the plasmasphere temporal variation from the Aberystwyth measurements, the diurnal plasmasphere variation was neglected, so that the plasmasphere TEC variation was represented by a scaling factor and a line-of-sight function:
  \( P_{\alpha}(\phi_{\alpha}, \epsilon_{\alpha}, t_{\alpha}) = A_{\alpha} L_{\alpha}(\phi_{\alpha}, \epsilon_{\alpha}) \)

Single parameter (A) is determined from data, for plasmasphere TEC.
1998, day 090; 30-degree elevation threshold. Still night-time dispersion in VTEC, but with reduced envelope. Negative VTEC excursion eliminated.
The First SCORPION of All

From Mazzella et al., 2002

1999, day 090, and 1999, day 096.
The First SCORPION of All

• Limitations of plasmasphere representation became evident by 2000:
  a) Diurnal time variation of plasmasphere TEC
  b) Broader latitudinal extent of significant plasmasphere densities, with depletion/replenishment cycle
  c) Considerations of increasing solar flux
1. Development resumed in 2004, for SBIR Phase-I
2. Intended to address:
   a) Diurnal and day-to-day time variation of plasmasphere TEC
   b) Structure of geomagnetic field (not simple dipole)
   c) Ease of use
3. Development continued through SBIR Phase-II, completed in 2007
4. Results included:
   a) Model validations against SUPIM
   b) Data corroborations against Jicamarca radar, TOPEX/Jason-1 (ionosphere) TEC, LEO beacon (ionosphere) TEC
5. Representative results were presented at 2007 International Beacon Satellite Symposium (IBSS) at Boston College [Mazzella et al., 2007]
Simulation sites were separated by 15° in magnetic latitude and 90° in magnetic longitude. Southernmost site in each chain is at magnetic equator. Principal sites studied (circled) were DA-DD and CB (for Taiwan campaign).
Left: SCORE emulation (SCORPION without plasmasphere determination); latitude limit 45.5° for calibration (black tracks for MLAT panel).

Right: Full SCORPION utilization, with plasmasphere determination.

Blue = SUPIM simulation data; Red = derived TEC

Some residual discrepancy in ionosphere/plasmasphere partitioning.

SCORPION bias: -0.101324 (with relative bias constraints)

SCORE bias: 1.17849 (average, latitude-limited); -1.28225 (average, all-sky above 35° elevation)
Left: Full SCORPION utilization, with plasmasphere determination, at magnetic latitude = 15 degrees

Right: Full SCORPION utilization, with plasmasphere determination, at magnetic latitude = 30 degrees

Blue = SUPIM simulation data; Red = derived TEC

Note non-zero plasmasphere slant TEC baselines (here imposed from SUPIM).

DC/LowF10/Saturated SCORPION bias: 1.454356 (with relative bias constraints)

DB/LowF10/Saturated SCORPION bias: 0.715678
Although SCORE bias error only appears to be ~6 TECu (middle panel), the SCORE TEC also includes the plasmasphere TEC, so the bias error is ~14 TECu.

Left: SCORE emulation (SCORPION without plasmasphere determination).
Right: Full SCORPION utilization, with plasmasphere determination.

Blue = SUPIM simulation data; Red = derived TEC
Note non-zero plasmasphere slant TEC baselines (here imposed from SUPIM).
SCORPION bias: -6.8038784E-02 (with relative bias constraints)
SCORE bias: 13.9313
PSPH STEC (Plasmasphere Slant TEC) error primarily associated with baseline assignment. Arrows indicate TOPEX passes. Red dots indicate integrated densities from Jicamarca radar. Relative bias constraints were imposed.
SCORPION – IBSS 2007

From Mazzella et al., 2007

ANCON/JICAMARCA Aug 2002 - consecutive days (225, 226)
Red dots indicate integrated densities from Jicamarca radar.
Partitioning error possible for 2002-225 at midday.
Probable error in ionosphere/plasmasphere partitioning for 2002-226, with incomplete passes at end of day and associated higher multipath.
Relative bias constraints were imposed.
Here and the Plasmasphere
February 2007, New England

From Mazzella, 2009

Left: SCORE emulation for SCORPION (no plasmasphere); significant VTEC gradients apparent throughout day.
Right: Full SCORPION utilization
Relatively quiet geomagnetic conditions for about two weeks prior to data, allowing plasmasphere replenishment.
Compare to SUPIM case DD/LowF10/Saturated.
Case noted by Patricia Doherty in February 2007.
SCORE average (receiver) bias: -13.5381; SCORPION average (receiver) bias: -12.8414 (difference = -0.7417)
Here and the Plasmasphere

Plasmasphere Effects for North America

• Line-of-sight for 0° elevation
• IPP at 350 km altitude
• BPP at 1000 km altitude
• PPP at 1400 km altitude
• “LOS" label at 3800 km altitude (attains ~70% of plasmasphere TEC for solar minimum)
• Even eastward LOS extends equatorwards into plasmasphere (azimuth = 80.6°)

From Mazzella, 2009

Representative PPP altitude for this figure (1400 km) is approximately Jason-1 altitude. Azimuth = 80.6°; elevation = 0°.
IPP = Ionosphere Penetration Point
BPP = Boundary (Ionosphere/Plasmasphere) Penetration Point
PPP = (nominal) Plasmasphere Penetration Point
LOS "enters" plasmasphere (from below) ~30° from site (BPP); attains Jason-1 altitude ~35° from site (PPP).
Even "Eastward" LOS (depicted) extends equatorwards into plasmasphere, w. "LOS" marker ~15° equatorwards of site (still only near median plasmasphere altitude for Plasmasphere Slant TEC (PSTEC)).
At 3800 km: 95.7% of composite TEC; 70.5% of PSTEC (~4.7 TEC units)
SUPIM simulations for central US site: Hillsboro, Kansas; Noon local time at HBRK; elevation = 35°

TEC asymptote for poleward LOS from plasmapause penetration (SUPIM cutoff)

More gradual transition to asymptotic value for equatorward PEC at low solar flux, producing higher median altitude

a) F10.7 = 75; PEC(N) = 1.4 TECu (10% total); PEC(S) = 7.8 TECu (~33% total); median PEC altitude = 3800 km

b) F10.7 = 250; PEC(N) = 5.5 TECu (7% total); PEC(S) = 10.5 TECu (11% total); median PEC altitude = 1950 km
Here and the Plasmasphere

Plasmasphere Effects for North America

Low Solar Flux

From Mazzella, 2009

Low solar flux (75); ionosphere alone (IVTEC); composite ionosphere and plasmasphere (CVTEC)

H is used for IPP calculation; H+ΔH is used for slant-to-vertical conversion

(a) local noon (with H = 350 km, ΔH = 0 km)
(b) local midnight (with H = 350 km, ΔH = 65 km)

Can get good match for IVTEC versus True IVTEC, but not for CVTEC versus True CVTEC.

Plasmasphere introduces "bump" for CVTEC (composite VTEC) equatorward of site.

Underestimated CVTEC poleward of site, relative to True CVTEC (daytime only);

Underestimated CVTEC far equatorward of site is from mis-attributed "bump" TEC.
Here and the Plasmasphere

Plasmasphere Effects for North America
High Solar Flux

Converted Slant TEC Compared to True Vertical TEC (Noon)

Converted Slant TEC Compared to True Vertical TEC (Midnight)

H = 350 km, ΔH = 65 km

H = 250 km, ΔH = 0 km

From Mazzella, 2009

High solar flux (250);
ionosphere alone (IVTEC); composite ionosphere and plasmasphere (CVTEC)
(a) local noon (with H = 350 km, DH = 65 km)
(b) local midnight (with H = 250 km, DH = 0 km) <- note H change
Can get only limited good match for IVTEC versus True IVTEC, and also for CVTEC versus True CVTEC;
Ionosphere is principal source of STEC-to-VTEC error equatorward of site (associated w. "corner" in Cum STEC, at 1000 km)
SCORE and SCORPION typically use an elevation threshold of 35°.
Here and the Plasmasphere
Plasmasphere Effects for North America
Low Solar Flux

From Mazzella, 2009

Inverse portrayal, with differences displayed rather than individual variations.
Low solar flux (75); maximum slant TEC is ~60 TECu.
Ionosphere alone (IVTEC); composite ionosphere and plasmasphere (CVTEC)
(a) local noon (with H = 350 km, DH = 0 km)
(b) local midnight (with H = 350 km, DH = 65 km)
For association with range errors: 1 m <= 6.2 TECu (L1); 1m <= 3.7 TECu (L2)
Here and the Plasmasphere
Plasmasphere Effects for North America
High Solar Flux

\[
\begin{align*}
H &= 350 \text{ km}, \ \Delta H = 65 \text{ km} \\
H &= 250 \text{ km}, \ \Delta H = 0 \text{ km}
\end{align*}
\]

From Mazzella, 2009

Inverse portrayal, with differences displayed rather than individual variations.
High solar flux (250); maximum slant TEC is ~370 TECu.
Ionosphere alone (IVTEC); composite ionosphere and plasmasphere (CVTEC)
(a) local noon (with \(H = 350 \text{ km}, \ \Delta H = 65 \text{ km}\))
(b) local midnight (with \(H = 250 \text{ km}, \ \Delta H = 0 \text{ km}\)) <- note \(H\) change
Ionosphere itself is significant source of discrepancy, from high-altitude ionization
Here and the Plasmasphere

Plasmasphere Effects for North America
Considerations for slant factor:
– Effective values for H and ΔH would depend on plasmasphere content (and consequently upon phase of replenishment process); restrictions are less severe if plasmasphere is accounted for separately (leaving only ionosphere slant TEC for conversion).
– Direct inversion of standard slant factor formula for Hᵢ produces indeterminate result at zenith, with large variation near zenith.
– An elevation threshold of ~35° still appears necessary, even for an implementation such as SCORPION.
SUPIM simulation for Colima, Mexico (MLat=−27°).

Note: The minimum slant PEC (“PSPH STEC”) is almost 2 TECu.
There and Everywhere

• The Plasmasphere Baseline Problem:
  – For regional observations at lower latitudes, an omnipresent plasmasphere contribution can exist in all directions.
  – The uniform component of this plasmasphere contribution is indistinguishable from a receiver bias, because of the occurrence of the terms \((B_\alpha + B_r) + P_\alpha(\phi, \epsilon_\alpha, t_\alpha)\) in the correction for the measured slant TEC.

• Two resolution methods were proposed at IBSS 2007:
  – a) latitudinal chain of sites
  – b) temporal sequence, commencing from a period of plasmasphere depletion

• A latitudinal chain is demonstrated here.

Plasmasphere baseline problem was displayed for Ancon data, and DA, DB, DC simulations for 35° elevation threshold and 1000 km ionosphere/plasmasphere boundary, station location would need to be within 10° of plasmapause to avoid baseline ambiguity.
Compare Colima to a poleward site (La Paz); Common IPP, but plasmasphere regions are different.

Local vertical PEC at the IPP is not directly available from measurements, but only from SCORPION plasmasphere determination.

Align Colima VPEC ("PSREP VTEC") values to (reference) La Paz VPEC (here selected over common 1-deg MLat band).

Bias shift is required after baseline correction is imposed, to retain constant \((B_\alpha + B_r) + P_{\alpha}(\phi_{\alpha},e_{\alpha},t_{\alpha})\).
SUPIM simulation (blue) and SCORPION results (red), with adjusted plasmasphere baseline (1.77) and corresponding bias shift.

From Mazzella, 2012

There and Everywhere

SUPIM Simulation (blue) and SCORPION (red)
Need a chain of stations, because La Paz cannot be presumed to have a zero baseline.

PEC still detectable at Neah Bay (consonant w. SCORPION Bellevue studies); end of chain for Bishop et al. (2009). Extended chain poleward to Fairbanks, Alaska (to assure proximity to plasmapause).

Jason-1 provided TEC comparison (essentially ionosphere component only), for 08-Apr-2007; calibrated against LEV2, rather than either CHI4 or KOD2 (effect of initial Jason-1 TEC transient).
There and Everywhere

• Processing aspects:
  – Data primarily from CORS (except HOLB from IGS).
  – Pre-processing was performed using ARL GPS Toolkit [Tolman et al., 2004].
  – Two days combined (08 Apr 2007 and 09 Apr 2007), for selection of full satellite passes.
  – Additional treatment to diminish residual effects of multipath [Kee and Parkinson, 1994; Andreasen et al., 2002].
Northern half of chain on left; southern half of chain on right.
Constant Mag Local Time and TEC ranges (top, middle panels), but shifted MLat ranges. Smooth, generally consistent (inter-station) IVEC profiles, until equatorial anomaly region. Significant slant PEC for NEAH; would require latitude limit for processing by SCORE.
Varying range for IVEC along chain, but constant PEC upper limit; Shifted MLat ranges for each row.

Some IVEC discrepancy for Level Island/Holberg.

Largest inter-station baseline difference is 0.36 TECu; largest baseline correction is 0.78 TECu (LPAZ).

Plasmasphere is likely in replenishment phase, after activity on 01 Apr 2007.
Evaluating the Calibrations

- Standard deviations up to 2.6 TECu (10 stations).
- Discrepant pattern for GNAA.

From Mazzella, 2012

Coarse Acquisition (C1) GPS signal used, from absence of Precise Code (P1) signal in RINEX files.

GNAA pattern for relative satellite biases is similar to P1 sites.
Evaluating the Calibrations

- Standard deviations below 1.1 TECu (6 stations).

From Mazzella, 2012

Precise Code (P1) signal available in RINEX files.
Evaluating the Calibrations

The SCORE bias error trend continues equatorward, as noted in previous near-equatorial cases (with similar performance for other calibration methods that disregard plasmasphere effects).

From Mazzella, 2012

Left: Extending Lunt bias validations to chain (subset), trend in bias errors is evident for SCORE (SUPIM simulations); Slight possible error trend for SCORPION.

Right: Differences for SCORE minus SCORPION receiver biases are displayed for measured data.

Equatorward trend is evident, with initial high-latitude transition also appearing.

Error bars are derived from SCORE/SCORPION minimization quantity ("E"), normalized.
Evaluating the Calibrations

- SCORPION and SCORE comparisons to Jason-1
- Jason-1 calibration against LEV2 IEC, to avoid initial transient for Jason-1 pass, while also excluding plasmasphere.
- Derived Jason-1 bias: 5.6 TECu.
- GPS data locally bracket Jason-1 pass segments, within ±0.5 hour (MLT) and within ±7.5° of site geographic longitude.

MLT (magnetic local time) and longitude ranges allow some UT (Universal Time) variation into GPS data selections.
Evaluating the Calibrations

- Possible corroboration of SCORE bias error trend, from relative change in SCORE and Jason-1 TEC levels near LPAZ and HER2.

- Jason-1 TEC tends to remain close to SCORPION IEC, but sometimes slightly greater than SCORPION CVTEC.

From Mazzella, 2012

Ionosphere VTEC (=VIEC) (bottom panel); plasmasphere VTEC (=VPEC) (SCORPION only) (top panel); composite VTEC (VIEC+VPEC) (middle)

Jason-1 calibration against LEV2 VIEC, to avoid initial transient for Jason-1 pass, while also excluding plasmasphere.

Derived Jason-1 bias: 5.6 TECu.

GPS data locally bracket Jason-1 pass segments, within ±0.5 hour (MLT) and within ±7.5° of site geographic longitude.
Evaluating the Calibrations

• SCORPION Comparisons to IONEX: CODE, JPL, UPC
• CODE: Center for Orbit Determination in Europe of the Astronomical Institute of the University of Bern
• JPL: Jet Propulsion Laboratory of the California Institute of Technology
• UPC: Research group of Astronomy and Geomatics of the Technical University of Catalonia
• All use single-layer ionosphere representation, with slant conversion altitude of 450 km.
• UPC uses two layers (399 km, 1079 km) for analysis.
Evaluating the Calibrations

- Contravening latitudinal gradients for some of the GPS data segments are a consequence of the temporal variation of TEC overwhelming the normal latitudinal gradient.

From Mazzella, 2012

Same format as comparison to Jason-1; Data selection for MLT = -6.

JPL: highest VTEC; UPC/CODE VTEC cross-over, and closer to SCORE VTEC than to SCORPION VIEC or CVTEC (may be more a consequence of standard determination of equivalent vertical TEC from slant TEC than influence of bias determinations).
Evaluating the Calibrations

- SCORPION IEC and CVTEC for MLT = 0 show smooth latitudinal variation, in contrast to SCORE "sawtooth".
- SCORE TEC pattern also corresponds to apparent CVTEC shown for North America cases

From Mazzella, 2012

Same format as comparison to Jason-1; Data selection for MLT = 0.
Evaluating the Calibrations

- Contravening latitudinal gradients for some of the GPS data segments are a consequence of the temporal variation of TEC overwhelming the normal latitudinal gradient.

From Mazzella, 2012

Same format as comparison to Jason-1; Data selection for MLT = 6.
Evaluating the Calibrations

SCORPION IEC and Composite VTEC for MLT = 12 show smooth latitudinal variation, in contrast to SCORE "sawtooth".

SCORE TEC pattern also corresponds to apparent Composite VTEC shown for North America cases.

From Mazzella, 2012

SCORPION Comparisons to IONEX: CODE, JPL, UPC

Same format as comparison to Jason-1; Data selection for MLT = 12.

CODE: Center for Orbit Determination in Europe of the Astronomical Institute of the University of Bern
JPL: Jet Propulsion Laboratory of the California Institute of Technology
UPC: Research group of Astronomy and Geomatics of the Technical University of Catalonia

All use single-layer ionosphere representation, with slant conversion altitude of 450 km.
UPC uses two layers (399 km, 1079 km) for analysis.
Evaluating the Calibrations

• General Assessments:
  – CODE IONEX TEC values tend to be larger than those for UPC at lower latitudes;
    • Reverse occurs for higher latitudes;
  – JPL IONEX TEC values are larger than either of these, as well as generally being larger than the SCORE and SCORPION values.
  – Both the CODE and UPC IONEX TEC values tend to be closer to the SCORE equivalent vertical TEC than to the SCORPION composite vertical TEC;
    • May be more a consequence of standard determination of equivalent vertical TEC from slant TEC than influence of bias determinations.
Evaluating the Calibrations

SCORPION ("Emulation") representation of equivalent vertical plasmasphere electron content, using standard SCORE slant factor, reproduces "sawtooth" effect for both plasmasphere and composite TEC.

Top panel changed to equivalent vertical plasmasphere TEC, converted as for ionosphere. Sawtooth pattern appears; the problem involves the mapping to IPP location as well as the slant factor.
Here and the Plasmasphere (Reprise)
Plasmasphere Effects for North America
Low Solar Flux

Additional designation of elevations above 35 degrees (vertical green lines). Derived composite VTEC (CVTEC) displays similarity to individual "sawtooth" features.

Low solar flux (75);
ionosphere alone (IVTEC); composite ionosphere and plasmasphere (CVTEC)
H is used for IPP calculation; H+ΔH is used for slant-to-vertical conversion
(a) local noon (with H = 350 km, ΔH = 0 km)
(b) local midnight (with H = 350 km, ΔH = 65 km)
Can get good match for IVTEC versus True IVTEC, but not for CVTEC versus True CVTEC.
Plasmasphere introduces "bump" for CVTEC (composite VTEC) equatorward of site.
Underestimated CVTEC poleward of site, relative to True CVTEC (daytime only);
Underestimated CVTEC far equatorward of site is from mis-attributed "bump" TEC.
Conclusion

1. Issues addressed by SCORPION:
   a) Systematic plasmasphere-induced bias errors
   b) Partitioning of TEC into ionosphere and plasmasphere contributions, affecting determination of local vertical TEC (including resolution of "sawtooth" gradients)
   c) Plasmasphere baseline alignment method, for potential step discontinuities across stations for plasmasphere latitudinal gradients
   d) Possible use of relative satellite biases, if multipath residuals can be avoided or treated adequately

2. Caveats for other ionosphere-based calibration methods (e.g., SCORE):
   a) Latitudinal bias error trend associated with plasmasphere content
      1) Associated errors for plasmasphere measurements using GPS minus LEO TEC, or two-station GPS
      2) Need for latitudinal exclusions for mid-latitude calibrations
   b) Temporal bias error variation associated with plasmasphere replenishment (and sudden storm depletions)
   c) Apparent enhanced TEC gradients from compression of plasmasphere gradients using standard slant factor and IPP mapping

3. Validation of calibration methods against models can be very informative
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• The figures were prepared using the Generic Mapping Tools (GMT) graphics [Wessel and Smith, 1998].
Acknowledgments

- CORS GPS data: United States Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) FTP site cors.ngs.noaa.gov [Noll, 2010]
- IGS GPS and IONEX data: Crustal Dynamics Data Information System (CDDIS) at the NASA Goddard Space Flight Center FTP site cddis.gsfc.nasa.gov [Dow et al., 2009]
- IONEX processing code: University of Bern FTP site ftp.unibe.ch [Schaer et al., 1998].
- Jason-1 data: Physical Oceanography Distributed Active Archive Center of the Jet Propulsion Laboratory FTP site podaac.jpl.nasa.gov [Berwin, 2003]
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