This study was prompted by John Bosco Habarulema's seminar in 2013, showing the extended GPS receiver coverage for Africa. The results were published, with some revisions and refinements, in 2017 (Mazzella, A. J., J. B. Habarulema, and E. Yizengaw (2017), Determinations of ionosphere and plasmasphere electron content for an African chain of GPS stations, Ann. Geophys., 35, 599-612, DOI:10.5194/angeo-35-599-2017).

Sheffield University Plasmasphere Ionosphere Model (SUPIM) [Bailey and Balan, 1996] results are displayed for 14:00 Local Time at site TEZI meridian, for partially replenished plasmasphere.


Ionosphere-Plasmasphere "boundary" at 1000 km altitude (inner red semi-circle). Gray semi-circles for radii 10,000 km, 15,000 km, 20,000 km, and 25,000 km.

GPS orbit radial distance at 26,560 km (outer red semi-circle).
Subset of available GPS sites for 2011.
SUPIM simulation sites (indicated in red): HNUS, TEZI, MOIU, FRSN.
Small circles: Viewing region for ionosphere (350 km altitude, 35° elevation threshold); span is 8°.
Large circles: Viewing region at base of plasmasphere (1000 km altitude, 35° elevation threshold); span is 20°.
Latitudinal variation of plasmasphere is compressed by mapping to ionosphere penetration point (IPP), for composite TEC conversion to vertical.
GRHM and KERG were added for supplementary corroborations.
Progressing South to North, in columns.

"Partial replenishment" plasmasphere condition modelled (5-day replenishment period): $F_{10.7} = 86$, $F_{10.7}\text{Avg} = 97.8$, $Ap = 4$

(Day 2011 206 appears in lower caption for delay in synchronizing model to GPS ephemeris, from late local time in model evolution.)

Equivalent Vertical TEC (VTEC) is shown against magnetic Local Time at the Ionospheric Penetration Point (IPP), for an altitude that varies somewhat from site to site, based on the local vertical ionosphere profile. The lower panel displays the magnetic latitude at the IPP, allowing an association of VTEC gradients with latitude, superimposed on the diurnal variation.

Broader latitudinal variation evident across sites.

Some VTEC variation latitudinally and temporally during nighttime.
Ionosphere-Plasmasphere boundary defined at 1000 km altitude.
Standard display results for SCORPION: Geomagnetic latitude in bottom panel; Ionosphere vertical TEC in middle panel; Plasmasphere slant TEC in top panel.
(Day 2011 206 appears in lower caption for delay in synchronizing model to GPS ephemeris, from late local time in model evolution.)
Can get smoother (but not completely smooth) ionosphere VTEC by separating plasmasphere contribution.
Larger apparent latitudinal gradient for composite TEC (previous slide) at each site is attributable to plasmasphere.
This is a schematic for the conversion of slant (line-of-sight) TEC to vertical TEC, displayed for a site latitude approximating that for Hermanus (HNUS), for line-of-sight elevations of 35°.

Slant IEC + Slant PEC -> converted to Vertical -> Composite Equivalent Vertical TEC (CEQV)

IVTEC + PIPV (= PSREP VTEC) = Composite Vertical TEC (at IPP) (CVTC)

For the standard conversion, without TEC partitioning between the ionosphere and plasmasphere, the Slant IEC (Ionosphere Electron Content) plus Slant PEC (Plasmasphere Electron Content) are converted to Composite Equivalent Vertical TEC (CEQV) at the IPP, with a significant geographical displacement for the plasmasphere contribution. Alternatively, the ionosphere VTEC, derived from the Slant IEC, can be combined with the local plasmasphere vertical electron content (PIPV), using the plasmasphere representation, to obtain the Composite Vertical TEC at the IPP (CVTC).
Local time and latitude scale lengths essentially define the "conjunction" regions for comparison of equivalent vertical ionosphere TEC.

Individual satellite biases are determined from the consistency of equivalent vertical ionosphere TEC values at conjunctions.

Plasmasphere representation contains parameters determined by the minimization process.

Possible ambiguity remains between bias and spatially constant component of plasmasphere slant TEC; requires latitudinal chain of stations for resolution.

Method is implemented in SCORPION program (SCORE for Plasmasphere and Ionosphere, based on Self Calibration Of Range Error (SCORE)).
Processing the GPS Data

1) Retrieve the GPS data
   Sites were from three different GPS networks: UNAVCO, IGS, TrigNet.
   Two contiguous days were retrieved and combined, to obtain complete passes
   spanning at least 24 hours.
2) Retrieve the ephemeris data (also for two days, combined).
3) Extract GPS data for each satellite pass, combined with azimuth and elevation values.
   Processing steps were performed using ARL GPS Toolkit [Tolman et al., 2004].
   Incomplete passes (or passes outside specified time interval) are discarded.
   Phase discontinuities are corrected (also using ARL GPS Toolkit).
4) Review GPS pass files
   Some automated checks are performed if visual check is skipped.
5) Generate database files (typically one per satellite, but alternatively one per satellite
   pass).
   Additional parameters (e.g., IPP latitude/longitude/local time) are included, to expedite
   bias calibration.
   Phase alignment with code signal is also performed, separately for each satellite pass,
   for multipath reduction.
6) Determine and apply multipath consistency corrections (to be explained later).
7) Perform bias calibration and plasmasphere determination.
8) Generate TEC evaluation plots (and possibly other diagnostic plots).
Treating Multipath

Arises from reflection environment for GPS signals arriving at receiver antenna.
Code signal multipath is larger than phase multipath (which is essential negligible).
Phase signal has cycle ambiguity, in addition to bias, with different cycle ambiguity for each satellite pass.
Aligning phase signal to code signal over entire pass reduces cycle ambiguity, and produces smoother TEC measurements for calibration.

$SA_i = SP_i + <SR_i - SP>$, for code (range) signal $SR_i$, phase signal $SP_i$, with $<SR_i - SP>$ denoting average over satellite pass.

Some residual cycle ambiguity is possible for each pass, especially for shorter passes; addressed by multipath consistency conditions [Kee and Parkinson, 1994; Andreassen et al., 2002].
Satellite sky tracks, with multipath signal superimposed.
Satellite sky tracks are indicated in red; multipath amplitudes (positive and negative) are indicated in green, with scaling of 10 TEC units per grid degree. Multipath is typically higher for low satellite elevations.

The elevation threshold for GPS satellite observations is evident in the display, as is the satellite coverage gap poleward of the GPS station, arising from the inclination of GPS satellite orbits.

Multipath correction has a significant role if "generic" relative satellite biases are used, rather than site-specific relative biases, or if multiple passes for a satellite, along different satellite tracks, occur within a calibration data set.
Second and third GPS stations in chain.
Fourth and fifth GPS stations along the chain.
TEZI has higher sampling rate (1/15-sec), versus standard rate for TDOU (1/30-sec).
Sixth and seventh GPS stations along the chain.
UKAM has higher sampling rate (1/15-sec), versus standard rate for NURK (1/30-sec).
Note effects of apparent obstructions near horizon.
Eighth and ninth GPS stations along the chain.
Note the transition of the GPS satellite coverage gap from the south to the north.
Tenth and eleventh GPS stations along the chain.
Corrections are determined and applied for individual passes.
The supplementary condition is different from the previously published version
[Andreasen et al., 2002].

Multipath Consistency Correction

- Minimize \( E = \sum_{\alpha} \sum_{\beta} \sum_{\alpha} \sum_{\beta} W_{\alpha,\beta} \ |(M_{\alpha} - m_{\alpha}) - (M_{\beta} - m_{\beta})|^2 \), where \( M_{\alpha, \beta} \) are pointwise multipath values for distinct satellite passes \( \alpha, \beta \), and \( m_{\alpha}, m_{\beta} \) are pass-wise multipath alignment values. The weight factor \( W_{\alpha,\beta} \) depends on the angular distance between compared samples \( i, j \).

- Because the alignment values always appear as paired differences \( (m_{\alpha} - m_{\beta}) \), a supplementary condition is required. This has been defined as: \( \sum_{\alpha} N_{\alpha} \cdot m_{\alpha} \cdot \sin(\varepsilon_{\alpha})^2 = 0 \), where \( N_{\alpha} \) is the number of samples and \( \varepsilon_{\alpha} \) is the peak elevation for each satellite pass \( \alpha \).
Requirements for Initial SCORPION Analysis for Africa

- Latitudinal chain, for plasmasphere electron content (PEC) baseline (resolving baseline/bias ambiguity).
- Quiet extended period, allowing plasmasphere replenishment.
- Quiet day for analysis, for VTEC equality at conjunctions.

Evaluated days from 16 Apr 2011 to 04 Aug 2011; reduced to 07 Jul 2011 to 04 Aug 2011 by missing data.
Finally reduced to 24 Jul 2011 by missing data and activity.
For each individual plot:

Bottom panel - magnetic latitude at Ionospheric Penetration Point (IPP)
Middle panel - ionosphere equivalent vertical TEC
Top panel - plasmasphere slant TEC

KERG included, to validate reference level for plasmasphere baseline

Slight negative ionosphere TEC excursions for KERG (Kerguelen Islands), from residual multipath for pair of passes for PRN 28.

Referenced calibrations were used for MFKG, TDOU, TEZI, UKAM, NURK, MOIU, BDAR, FRSN; not HNUS, SUTH, ARMI.

Plasmasphere baseline values were set progressively along chain, from southernmost site (HNUS), and are displayed above the plots for the affected sites.
(Note: ARMI was subsequently processed using a referenced calibration against MOIU, with small effects for BDAR and FRSN.)
Plasmasphere TEC is Vertical Plasmasphere Electron Content, at Ionospheric Penetration Point, rather than Plasmasphere Slant Electron Content.

One-degree bands are used for TEC correspondence.

Plasmasphere baseline alignment has already been performed, with compensatory bias adjustment.

The latitudinal progression for the Vertical Plasmasphere Electron Content across sites is more consistent and the diurnal pattern is more evident.
Locations could not be determined for some sites listed in IONEX files, for survey of IGS, CORS, UNAVCO, and TrigNet: CODE(31), ESA(4), JPL(7).

Apparent coverage gaps for latitudes ~-15° and ~-10° for CODE; ~-15° and ~-10° for ESA; ~-15°, ~-10°, and ~10° for JPL.

Latitudinal profiles derived from these maps are displayed with the SCORPION results on subsequent slides, but, for some regions, the map coverage arises from the interpolation for non-overlapping sites.
Plasmasphere VTEC is Vertical Plasmasphere Electron Content, at the Ionospheric Penetration Point, rather than Plasmasphere Slant Electron Content observed from the GPS site.

The Ionosphere Equivalent Vertical TEC is displayed in the bottom panel, the Vertical Plasmasphere Electron Content at the Ionospheric Penetration Point is displayed in the top panel, and the Composite Equivalent Vertical TEC (CEQV) at the Ionospheric Penetration Point is displayed in the middle panel.

Data selection criteria: ±0.5 hr for specified Magnetic Local Time (MLT), ±7.5° relative to site geographic longitude.

Magnetic latitudes (top bar) are for mean magnetic longitude of sites (99.61°, positive East).

Variable ionospheric electron content trends (contrary to overall latitudinal trends) are attributable to temporal (and longitudinal) variation of ionosphere.

IONEX (global vertical TEC map) files from three analysis centers are displayed:
- codg = Center for Orbit Determination in Europe/Astronomical Institute of the University of Bern (CODE/AIUB)
- esag = European Space Agency/European Space Operations Center (ESA/ESOC)
- jplg = Jet Propulsion Laboratory (JPL)

A fourth analysis center (upcg = Research group of Astronomy and Geomatics of the Technical University of Catalonia), which was used by Mazzella (2012), was not used here, because only data with some technical problems were available for this
day. (Note: These problems were resolved for the subsequent publication.)
This sequence of slides will display the latitudinal profile at intervals of two hours in magnetic local time (MLT; $6 \leq MLT \leq 24$).

IONEX values are true vertical TEC at each latitude, in segments corresponding to the longitudes of the individual sites. Because there is no ionosphere/plasmasphere partitioning for the IONEX values, these values are the same for the bottom and middle panels.

SCORPION plasmasphere error bars are assigned as the square root of the maximum plasmasphere slant TEC for each site (although the errors are expected to be somewhat smaller); SCORPION composite TEC error bars are calculated from the mean residual calibration errors and the assigned plasmasphere error (square root of the sum of the squares).
Comparison to Boston College Institute for Scientific Research
TEC Determinations

• Calibrated by applying relative satellite biases, and determining receiver bias by minimizing the TEC variability for 02:00 - 06:00 Local Time [Valladares et al., 2009].

• Applied to four stations: HNUS, TEZI, MOIU, FRSN; used 24-hour UT period (0-24).

• Uses composite ionosphere and plasmasphere TEC, converted to equivalent vertical TEC.
Comparison station locations in red (same as SUPIM sites)
Operationally, Composite Equivalent Vertical TEC (CEQV) is the most consistent measurement for comparison to the ISR results.

Composite VTEC (CVTC) is the value more closely corresponding to true vertical TEC.

Comparison to BC ISR: TEC
Comparison Types

• Comparisons include:
  - ISR VTEC / SCORPION Ionosphere VTEC
  - ISR VTEC / SCORPION Composite Equivalent Vertical TEC (CEQV: composite slant ionosphere plus plasmasphere, converted to vertical)
  - ISR VTEC / SCORPION Composite VTEC (CVTC: ionosphere VTEC plus plasmasphere VTEC, evaluated at IPP)
Left: DGD TEC for ISR plot is tabulated VTEC.
Right: Ionosphere-only VTEC for SCORPION in middle panel.
Several TEC discontinuities appear for ISR results, contributing to TEC profile irregularities.
Some distinct differences for satellite tracking, from MLat panel comparisons (separate from selected time coverage).
Similar peak values for ISR VTEC versus SCORPION IVTEC.
Left: Similar latitudinally-induced variability for ISR VTEC versus SCORPION Composite Equivalent VTEC (CEQV).
Right: Note smoother VTEC profile for SCORPION Composite VTEC (CVTC) case. Generally lower ISR VTEC than either SCORPION CEQV or CVTC.
Left: DGD TEC for ISR plot is tabulated VTEC; larger apparent latitudinal variability than SCORPION ionosphere VTEC.
Right: Ionosphere-only VTEC for SCORPION in middle panel. Similar peak values for ISR VTEC versus SCORPION IVTEC.
Left: Similar latitudinally-induced variability for ISR VTEC versus SCORPION Composite Equivalent Vertical TEC (CEQV).
Right: Note smoother VTEC profile for SCORPION Composite VTEC (CVTC) case.
Lower ISR VTEC than either SCORPION CEQV or CVTC.
Left: DGD TEC for ISR plot is tabulated VTEC.
Right: Ionosphere-only VTEC for SCORPION in middle panel.
Some distinct differences for satellite tracking, from MLat panel comparisons (separate from selected time coverage).
Higher peak values for ISR VTEC versus SCORPION IVTEC.
Some of the differences between the BC ISR results and SCORPION would appear to indicate relative bias differences (MLT=14 to MLT=20), rather than just plasmasphere effects.
For the SCORPION results, note the smaller plasmasphere slant TEC gradients, relative to TEZI.
Left: Similar latitudinally-induced variability for ISR VTEC versus SCORPION Composite Equivalent Vertical TEC (CEQV).
Lower ISR VTEC than either SCORPION CEQV or Composite VTEC (CVTC); this may indicate the occurrence of the bias overestimation effect noted for SCORE in equatorial regions, as a plasmasphere effect [Mazzella et al., 2007].
Left: DGD TEC for ISR plot is tabulated VTEC, with larger apparent latitudinal variability than SCORPION ionosphere VTEC.
Right: Ionosphere-only VTEC for SCORPION in middle panel.
Possibly truncated ISR data set, toward end of day.
Similar peak values for ISR VTEC versus SCORPION IVTEC.
Slight differences for magnetic latitudes for Ionosphere Penetration Point, probably from different effective altitudes for IPP.

Left: Similar latitudinally-induced variability for ISR VTEC versus SCORPION Composite Equivalent Vertical TEC (CEQV).

Lower ISR VTEC than either SCORPION CEQV or Composite VTEC (CVTC); this may indicate the occurrence of the bias overestimation effect noted for SCORE in equatorial regions, as a plasmasphere effect [Mazzella et al., 2007].
A scale height extrapolation for the ionosphere topside could allow the determination of ionosphere electron content, to 1000 km altitude. The difference between the ionosonde and GPS TEC determinations is attributed to the plasmasphere [Belehaki, Jakowski, and Reinisch, 2003].
“GPS TEC” derived for Grahamstown receiver using BC/ISR method (ionosphere plus plasmasphere).

Upper panel: Ionosphere-only TEC derived from ionosonde (red dots) and SCORPION (colored lines).

The multi-colored lines, coding for latitude, are the SCORPION results for the Composite Vertical TEC (upper curve) and the Ionosphere Equivalent Vertical TEC (bottom curve), restricted to elevation angles above 60°.

Lower panel: “GPS TEC” minus “Ionosonde TEC” gives plasmasphere TEC (for elevations above 60°); result is compared to SCORPION vertical plasmasphere TEC.
Summary and Conclusions

- Primary chain of 11 sites was examined, spanning more than 50° of latitude through Africa, including equatorial region.
- Addressing plasmasphere content aids elimination of TEC gradient artifacts, in addition to original goal of improving calibration accuracy.
- Method was described for additional mitigation of multipath (also significant for use of relative biases).
- Further investigations are required for processing active ionosphere conditions.
- Additional ionosphere/plasmasphere comparisons remain to be examined.

The active ionosphere conditions significantly restricted the selection of dates for processing.
Acknowledgments

• SUPIM was provided by Graham J. Bailey.
• Development of SCORPION was conducted in collaboration with G. Susan Rao and supported by the Air Force Research Laboratory Space Vehicles Directorate under SBIR contracts FA8718-04-C-0000 and FA8718-05-C-0026 to NorthWest Research Associates.
• 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]
• TrigNet data (Grahamstown): ftp.trignet.co.za
• UNAVCO data are provided by the UNAVCO Facility with support from the National Science Foundation (NSF) and National Aeronautics and Space Administration (NASA) under NSF Cooperative Agreement No. EAR-0735158. UNAVCO data: data-out.unavco.org
• Ionosonde: Data: spase.info/SMWG/Observatory/GIRO [Reinisch and Galkin, 2011]; Analysis results: spase.info/VVO/NumericalData/GIRO/CHARS.P115M
• The figures were prepared using the Generic Mapping Tools (GMT) graphics [Wessel and Smith, 1998].
References