An overview of using multiple data sources to study ionospheric dynamics over the African sector

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African School on Space Science, Related Applications and Awareness for Sustainable Development of the Region:
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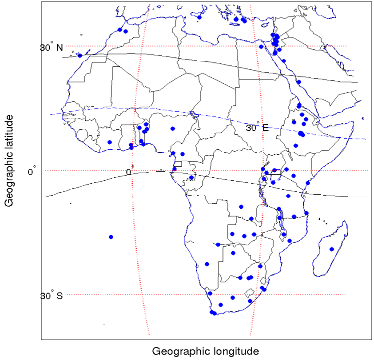
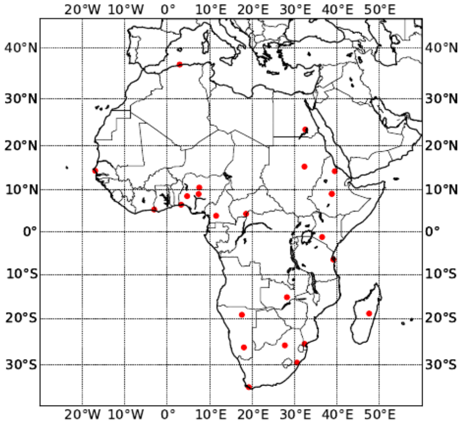
30 June - 11 July 2014

Africa's Ground-Based Instrumentation



IGS, AFREF stations



Credit to Stefan Lotz: Intermagnet, MAGDAS, AMBER, SANSA

Ground-based Instrumentation cont'd

Credit to Zama Katamzi

Station	Latitude (°)	Longitude (°)	Date Open (MMM-YYYY)	Date Closed/Status
Madimbo	-22.4	30.9	Jan 2008	Shut: Jul/Aug 2012
Louisvale	-28.5	21.2	Aug 2000	Still working
Grahamstown	-33.3	26.5	Jan 1973	Still working
Hermanus	-34.4	19.2	May 1971/Feb 1991	Still working
Illorin	8.5	4.55	Jun 2010	Still working
*Bangui	4.6	18.60	Feb 1958	Sept 1966
Bunia	1.5	30.2	Oct 1957	Nov 1960
*Cairo	30.0	21.2	Nov 1945	Sept 1946
Cape Town	-34.1	18.3	Sept 1944	May 1975
Dakar	14.8	-17.4	Jul 1957	Dec 1989
Djibouti/Arta	11.5	42.8	Oct 1951	July 1981
Elizabethville/Karavia	-11.60	27.5	Apr 1952	June 1960
*Fort Archambault	9.20	18.35	Jan 1969	Feb 1974
*Ibadan	7.4	3.9	Dec 1951	???
Johannesburg/Pretoria	-26.1	28.1	May 1946	Dec 1991
*Khartoum	15.55	32.58	Mar 1952	Mar 1954
*Kinshasa-Binza/Leopoldville	-4.5	15.2	Feb 1952	????
*Lwiro	-2.3	28.8	Feb 1952	Aug 1967
*Nairobi	-1.25	36.83	Mar 1952	???
Ougadougou	12.4	-1.5	Jun 1966	Dec 1989
*Tamanrasset	22.8	5.53	Feb 1956	???
*Togo/Dapango	10.8	0.4	Jul 1965	Feb 1967
*Tsumeb	-19.2	17.7	Jul 1957	Dec 1975

Operational: 3 (South Africa), 1 (Nigeria), 1 (Ethiopia), 1 (Kenya).

Available data

- Ionosonde: Measures bottomside ionosphere and gives a number of parameters, e.g. critical frequencies of different layers, electron densities.
- GNSS instrumentation: Provides a number of parameters such as TEC and is being used for a number of research disciplines (irregularities, scintillation, ionospheric TEC modelling, etc)
- Magnetometers: Geomagnetic data modelling, usage in explaining physical mechanisms for equatorial electrodynamics etc

Ultimate Aim

With the limited infrastructure, we intend:
To have a comprehensive modelling approach of describing ionospheric dynamics over the African sector

- Empirical and Physics based modelling techniques
- Accurately model ionospheric parameters (e.g. total electron content, electron density (N_e), foF2) during different conditions including storms

Global TEC models/measurements

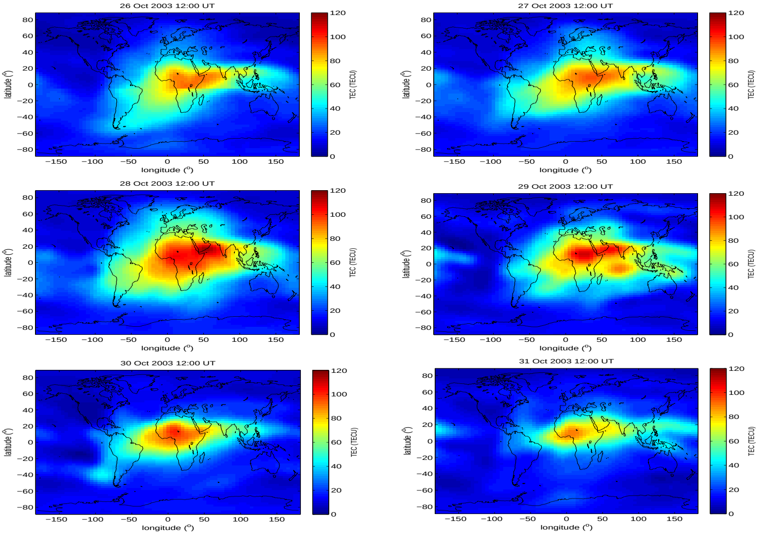
1. There are a number of TEC sources for global empirical/semi-empirical models (such as IRI and NeQuick), various techniques (both analytic and Tomographic), GAIM, CODE TEC maps etc
2. Ground based instruments such as GNSS receivers. Measurements can give global representation of ionospheric TEC
3. Specified latitude-longitude spacing followed by an appropriate interpolation method

Regional models

- Tend to be more accurate than global models (in a statistical sense)
- Region specific (easier to constrain) and so there are a number of them.

Global TEC maps

Data from: ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex



Katamzi and Habarulema (2014), Advances in Space Research

Conditions to be satisfied

Apart from the direct utilisation of ionospheric measurements, any model developed to predict/give modelled TEC values should reflect TEC changes during different circumstances

- Seasonal variations
- Diurnal variations
- TEC variability according to solar activity changes
- TEC variations during magnetic and ionospheric storms; a challenging task
- Spatial changes in TEC variability

What has been done: To simulate TEC values...

Factors which influence TEC have been categorised into three components; Periodic, Random and Positional components (e.g Stankov et al, 2001, A new method for total electron content forecasting using Global Positioning System measurements, Proc. ESA Space Weather Workshop, Noordwijk, The Netherlands, 169-172)

1. Periodic component, $P_c == S_v, D_v == D_n, H_r$
2. Random component, $R_c == R, A$
3. Positional component, $G_p == lat, long$

$$T_{simu} \equiv f(S_p) \quad (1)$$

$$S_p \equiv P_c, R_c, G_p \quad (2)$$

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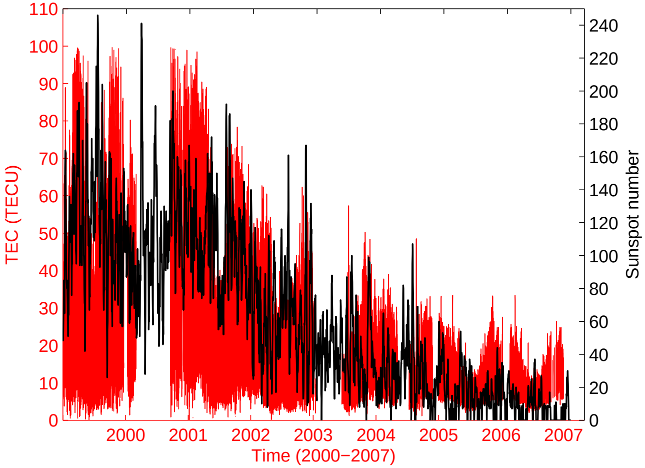
1. S_p: Standard parameters that influence TEC variability
2. S_v, D_v: Seasonal and diurnal variations respectively
3. R, A: Solar and magnetic activities respectively
4. G_p: Geographic location

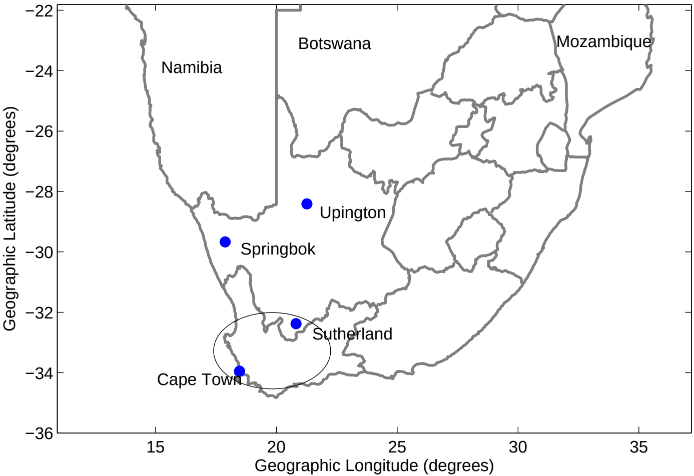
Main driver is the Solar Activity



Habarulema and Mckinnell (2012), Annales Geophysicae.

Single station modelling

Based on 2000-2004 data



Technique 1(a): Simple linear regression

- The dependent variable is modelled as a linear combination of independent variables.

  $$\mathrm{y} = f(\mathbf{X}, \beta)$$

  where $\mathbf{X}$ represents the independent variables and β are the unknown coefficients of the regression function, determined through the minimization of the squares of the deviations of the data from the model using the equation

  $$\mathbf{X_m}\beta = \mathbf{Y} \tag{3}$$

  where $\mathbf{X_m}$ is the matrix comprising of independent variables and $\mathbf{Y}$ is a column matrix of the dependent variable.
- The resulting equation for modelling a particular parameter is of the form

  $$y = \beta_0 + \beta_1 x_1 + ... + \beta_n x_n \tag{4}$$

  where $x_1, x_2, ...x_n$ are the parameters that influence TEC variability

Technique 1(b): Multiple linear regression

- A regression method that models the dependent variable as a product of independent variables raised to unknown powers was employed, i.e

$$y = Cx_1^{\beta_1} \times x_2^{\beta_2} \times ... \times x_n^{\beta_n} \tag{5}$$

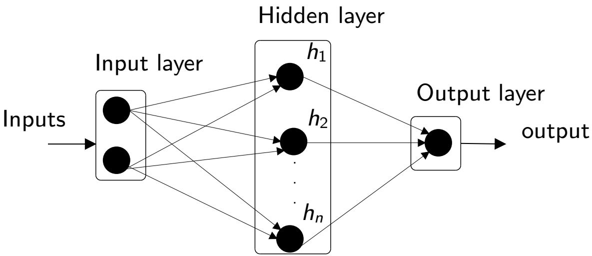
- The foundation of the above expression is linear regression analysis through the linear combination of logarithms of the considered parameters (Verő, 1980; Heilig et al., 2010) as,

$$\log(y) = d + \beta_1 \log x_1 + \beta_2 \log x_2 + ... + \beta_n \log x_n \tag{6}$$

where $d = \log C$. The underlying idea is that given the independent variables, $x_1, x_2, ..., x_n$, the dependent variable can be estimated from equations 4 and 5.

Technique 2: Non-linear approach: ANNs

Powerful tools that can be used to perform the tasks of learning and generalising the variational behaviours and patterns of parameters that exhibit non-linear characteristics through the input-output mapping process (Haykin, 1994).



A schematic illustration of a simple feed forward network

Data duration and processing

Data

- Hourly GPS TEC data for 2000-2004 over receiver stations located at Sutherland, SUTH (32.38°S, 20.81°E) and Cape Town, CPTN (33.95°S, 18.47°E)
- Regression and NN models are developed over SUTH and verified over CPTN

Data processing

- Required is to process data in a form that is compatible with both regression and neural network applications
- The D_n and H_r are split into cyclic components for data continuity, i.e

$$D_{ns} = \sin\left(\frac{2\pi \times D_n}{365.25}\right) \qquad D_{nc} = \cos\left(\frac{2\pi \times D_n}{365.25}\right) \tag{7}$$

$$H_{rs} = \sin\left(\frac{2\pi \times H_r}{24}\right) \qquad H_{rc} = \cos\left(\frac{2\pi \times H_r}{24}\right) \tag{8}$$

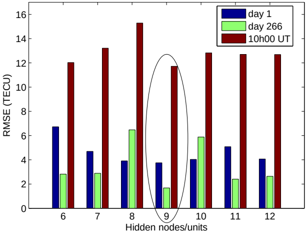
- Note that only P_c and R_c are used for single station TEC modelling

Choice of the architecture

Statistical methods are used e.g

$$\text{RMSE} = \left(\frac{1}{N} \sum_{i=1}^{N} (vT_m - vT_p)^2 \right)^{\frac{1}{2}} \tag{9}$$

where $i = 1, 2, ..., N$, N is the total number of observations for a given dataset, vT_m and vT_p are the measured and predicted vertical TEC values respectively.



NN models tested on 2000 data

- Varying hidden nodes while searching for optimum architecture
- Test and carry out statistical analysis
- For single station modelling (SSM), configuration is 6:9:1

Eqns for SLR and MLR models

The simple linear regression (SLR) model for modelling TEC variability over an hour interval from 2001-2004 was found to have the function

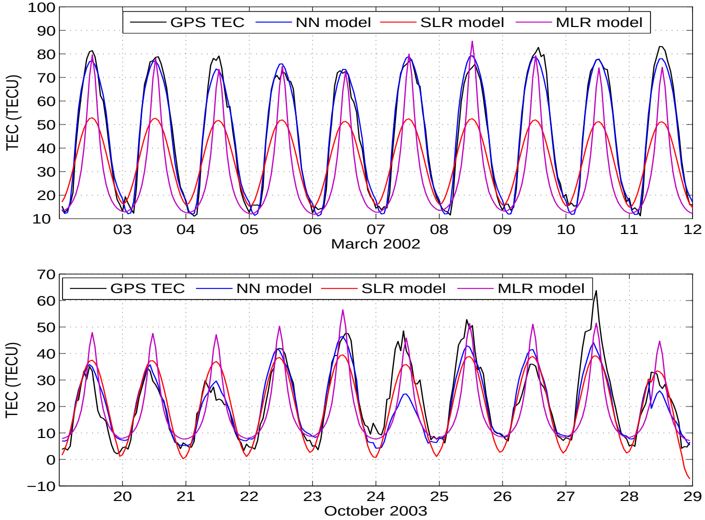
$$y = 3.6068 + 0.4372D_{nc} + 6.6253D_{ns} + 1.199H_{rs} - 18.3787H_{rc} + 0.2428R4 - 0.0994A8,$$

while the multiple linear regression (MLR) model for estimating TEC over the same location with the similar dataset becomes

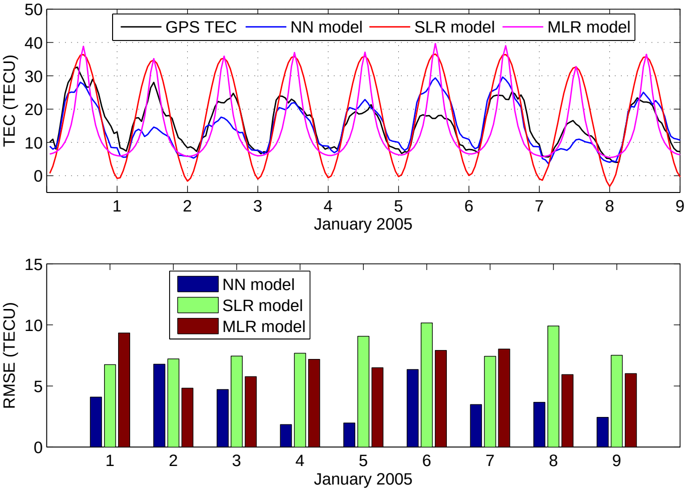
$$y \sim 0.834(D_{ns} + a)^{-0.0098} \times (D_{nc} + a)^{0.4081} \times (H_{rs} + a)^{-0.0068} \times (H_{rc} + a)^{-0.7569} \times (R4)^{0.6948} \times (A8 + b)^{-0.0831}$$

where y is TEC, $a = 1.2$ and $b = 0.1$ are constants added to the sine and cosine components of day number and hour; and A8 respectively to allow their respective logarithms to be taken.

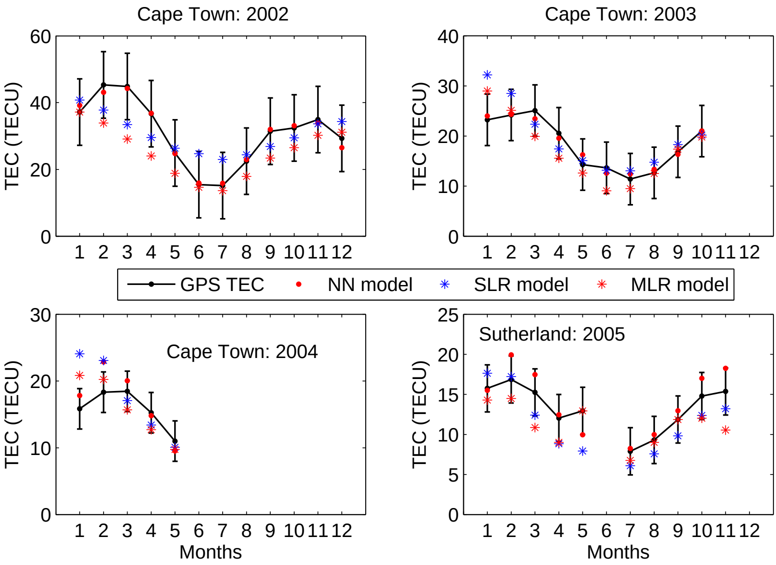
Modelled/interpolated results: CPTN



Extrapolation results



Monthly mean modelled TEC results



Summary for the two techniques

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Regression techniques

- Results show that SLR model generates almost similar diurnal variational pattern. At some times this approach generates negative TEC values which is not physically feasible.
- The MLR technique employed significantly underpredicts GPS TEC for the periods verified.

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Non-linear approach (neural networks)

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- Temporal extrapolation results show a “good performance” compared to SLR and MLR models, with accuracy lower relative to interpolation results

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Both techniques identify the decrease in monthly mean TEC values with the declining trend in solar activity

Linear regression versus neural networks?

- Linear regression analysis: Analytical functions that are probably easy to apply to other sets of identical data
- Neural networks: Results are in form of sets of extracted coefficients from data and probably takes a little longer to apply than regression models!

Each technique has its own advantages and disadvantages

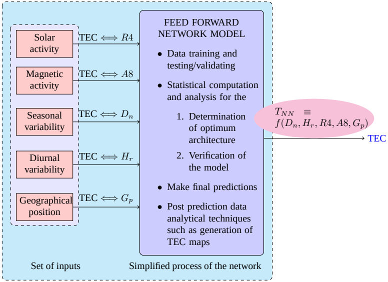
Final outcome of the feasibility study

Based on the obtained results, the neural network approach was adopted for regional TEC modelling and mapping.

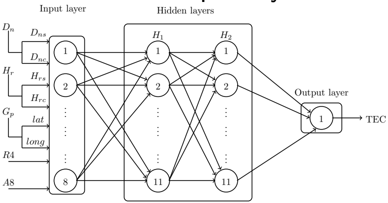
Model setup

Data period and architecture

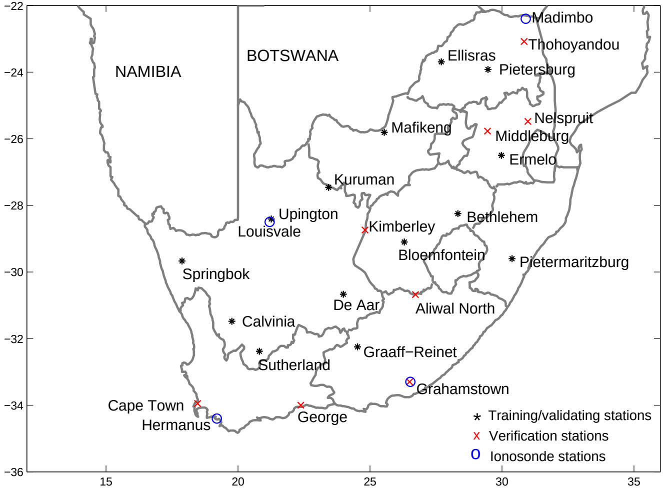
- Processed 1 minute vertical GPS TEC data for 2000-2006 over 14 stations
- Training data base consists of $\sim$ 17 million data points.
- Configuration; 8:11:11:1



1 input layer, 2 hidden layers and 1 output layer



GPS and ionosonde infrastructure



Regional TEC simulation

For spatial validations, three main steps are required

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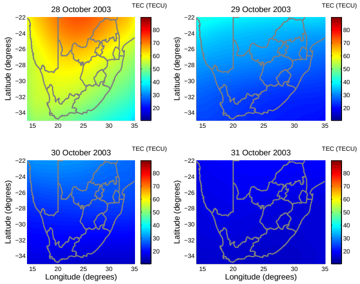
1. The model is used to artificially generate TEC predictions in latitude and longitude bins of dimensions $2^\circ \times 2.75^\circ$
2. Extrapolation: Purely based on single station models' approximations.
3. Interpolation: Biharmonic spline interpolation is applied at intervals of 0.1° in both latitudinal and longitudinal space (Sandwell, 1987)

$$\Delta^4 w(x) = \sum_{j=1}^{N} \alpha_j \delta(x - x_j) \qquad w(x_i) = w_i \tag{10}$$

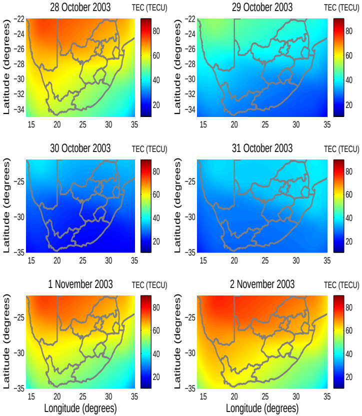
The general solution to the above equations is

$$w(x) = \sum_{j=1}^{N} \alpha_j \phi_2(x - x_j) \tag{11}$$

At 12h00 UT: 28 Oct-2 Nov 2003



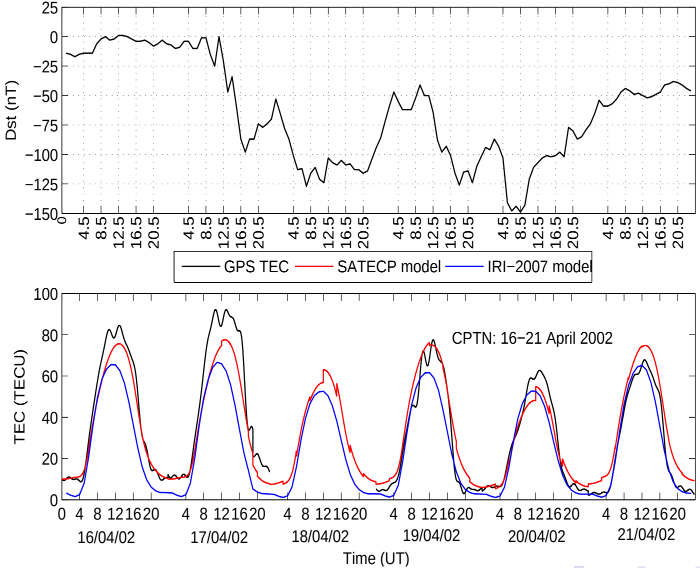
GPS TEC maps. Unavailability of archived historic data could not allow for the generation of GPS TEC maps for 1 and 2 Nov 2003



Reconstructed TEC maps

Habarulema et al., (2010), Journal of Atmospheric and Solar Terrestrial Physics

CPTN (16-21 April 2002): Positive storm effects not well modelled



To apply this over the entire African region

- A number of outstanding questions to be dealt with
    1. Reliable modelling of the storm time TEC behaviour. The current model performs poorly for positive storm effects even in midlatitudes— this is a point of concern
    2. Gathering enough historic data to describe the ionospheric behaviour
- Develop one comprehensive model or two separate models, i.e quiet time and storm time models....
- Supplement empirical model with Physics (theoretical) based model...

Positive storm effects in mid latitudes

Characterisation of the sources

As a result of magnetic storms, large amounts of energy are injected into the thermosphere-ionosphere system at high latitudes leading to an increase in thermospheric winds, sudden changes in neutral composition (caused by joule heating and particle precipitation) and the enhancement of equatorward gravity waves. The interaction between thermospheric gravity waves and the ionosphere generate Travelling Atmospheric Disturbances (TADs) which are manifested as TIDs

Assumption: Consider diurnal TEC as a plane wave

To a first approximation, equatorward propagating large scale TIDs are represented as a plane solitary travelling wave as

$$I(x, y, t) = A sin(\Omega t - k_x x - k_y y + \varphi_0) \quad (12)$$

where $I(x, y, t)$ is the total electron content, A is the wave amplitude, k_x and k_y are the x and y projections of the wave vector k, Ω and φ_0 are the angular disturbance frequency and initial disturbance phase respectively.

- Hunsucker, R. D., 1982. Atmospheric gravity waves generated in the high-latitude ionosphere, A review. Review of Geophysics 20, 293-315.
- Afraimovich, E. L., Palamartchouk, K. S., Perevalova, N. P., 1998. GPS radio interferometry of travelling ionospheric disturbances. Journal of Atmospheric and Solar Terrestrial Physics 60, 1205-1223.
- Valladares, C. E., Hei, M. A., 2012. Measurement of the characteristics of TIDs using Small and Regional Networks of GPS Receivers during the Campaign of 17-30 July of 2008. International Journal Geophysics.

SADM-GPS (interferometry) technique

The azimuthal propagation direction of the phase wave front ($\alpha(t)$) and TID's horizontal phase velocity, $v_h(t)$ can be computed using the following equations

$$\alpha(t) = tan^{-1}\left(\frac{I'_y(t)}{I'_x(t)}\right) \tag{13}$$

$$u_x(t) = \frac{I'_t(t)}{I'_x(t)}, \quad u_y(t) = \frac{I'_t(t)}{I'_y(t)} \tag{14}$$

$$u(t) = \frac{|u_x(t)u_y(t)|}{\sqrt{u_x^2(t) + u_y^2(t)}} \tag{15}$$

$$v_h(t) = u(t) + w_x(t)sin(\alpha(t)) + w_y(t)cos(\alpha(t)) \tag{16}$$

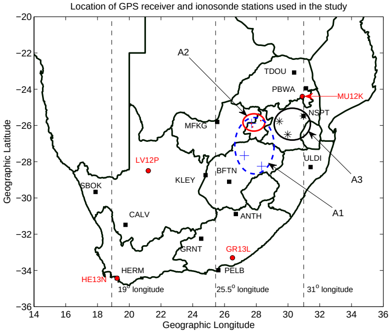
where $I'_x(t)$, $I'_y(t)$ and $I'_t(t)$ are the spatial and time derivatives, $u_x(t)$, $u_y(t)$ are the propagation velocities of the phase front along the x and y axes (assumed in east and north directions) in the frame of reference, and $w_x(t)$, $w_y(t)$ are the x and y projections of the sub-ionospheric intersection velocity.

Apply the statistical method to local data

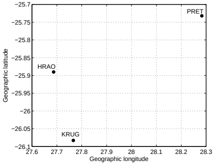
Specifically for positive storm effects during the events of

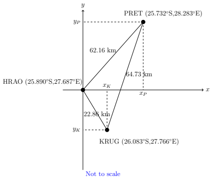
- 14-16 May 2005
- 25-27 September 2011

Data used



(a) Location of GPS receiver and ionosonde stations used in this study. The vertical dashed lines represent the approximate longitude sectors (19^o, 25.5^o and 31^o) at which the ratios of TEC to monthly median TEC (R_{TEC}) were computed for different stations during the period of 14-16 May 2005 and 25-27 September 2011. The BETH-KSTD-HARB (A1) array (inside the dashed blue ellipse), and KRUG-HRAO-PRET, A2 (red circle) and NSPT-MBRG-EMLO, A3 (black circle) arrays were used to estimate TID propagation characteristics on 15 May 2005 and 26 September 2011 respectively. The red filled dots represent ionosonde stations with labels in red text.





(b) An example illustrating one of the GPS arrays (KRUG-HRAO-PRET) used to study TID characteristics at a short scale with distances between the stations indicated in km.

Spatial and time derivatives

$$I'_t(t) = G_t = \frac{Y(t+dt) - Y(t)}{dt} \tag{17}$$

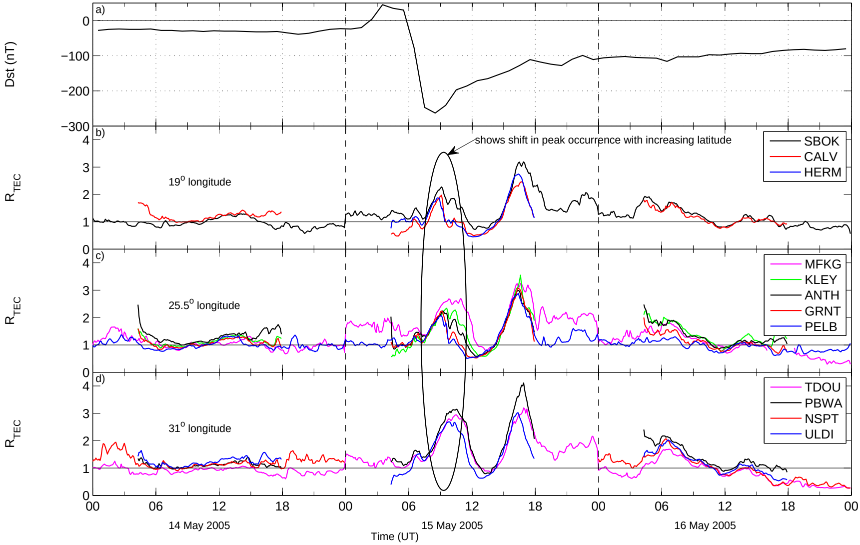
In this case, Y is the TEC perturbation at the reference station and dt is the sampling period of the data.

$$I'_x(t) = G_x = \frac{y_P(A_H - A_K) - y_K(A_H - A_P)}{x_P y_K - x_K y_P} \tag{18}$$

$$I'_y(t) = G_y = \frac{x_K(A_H - A_P) - x_P(A_H - A_K)}{x_P y_K - x_K y_P} \tag{19}$$

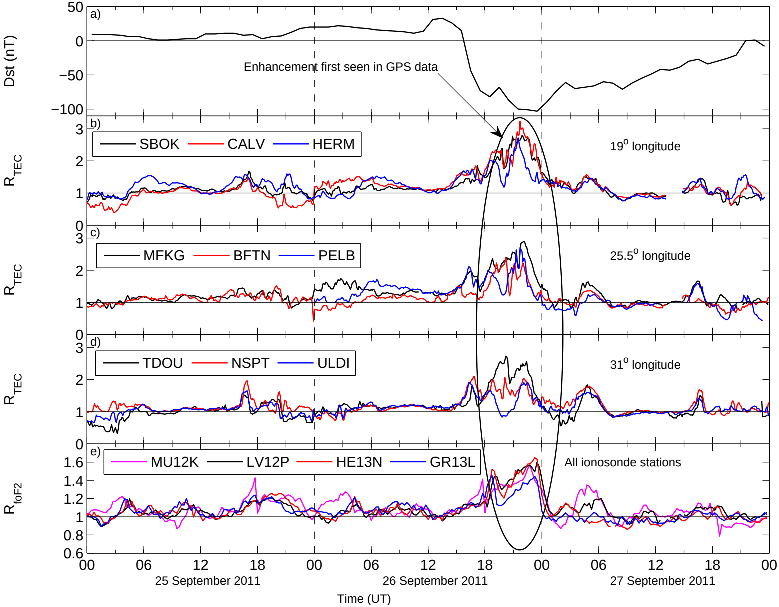
where A_H, A_K and A_P are the TEC perturbations at HRAO, KRUG and PRET respectively, x_P, y_P, x_K and y_K are the coordinate distances of PRET and KRUG from the reference station HRAO in a cartesian system.

Observed positive storm effects: 14-15 May 2005

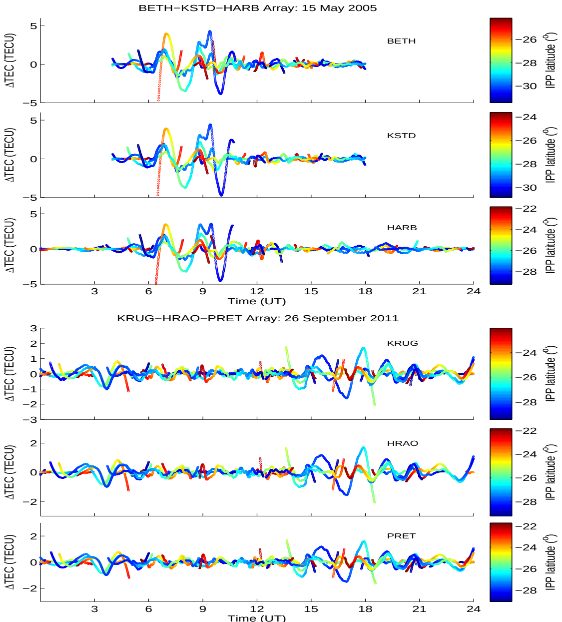


Habarulema et al., (2013), Journal of Geophysical Research

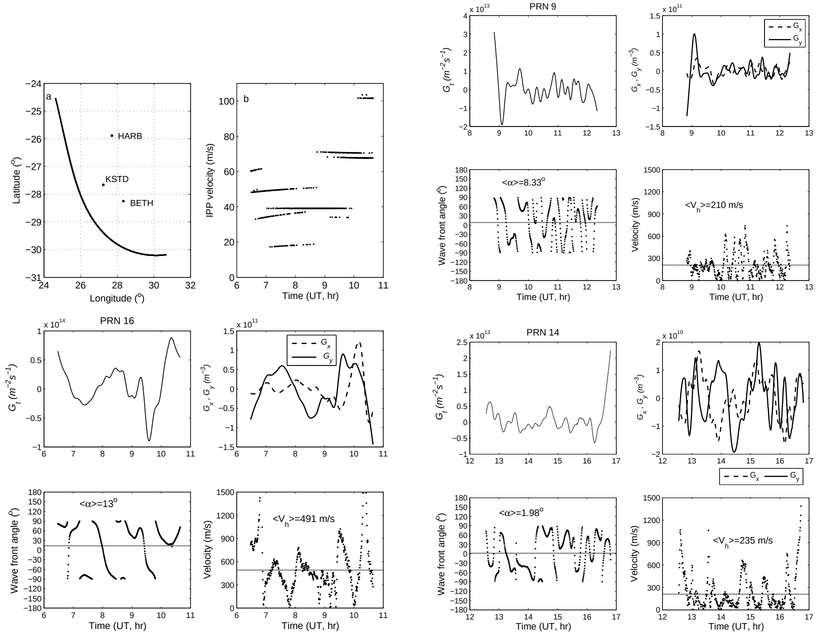
Observed positive storm effects: 25-27 September 2011



Identifying periods with possible TIDs



TID characteristics: 15 May 2005 and 26 September 2011



What next....

- Storm induced TIDs travel equatorward
- What about travelling ionospheric disturbances during quiet times???? We are currently doing a project to characterise TIDs during quiet time

Still no enough data to cover the entire African sector

Request: If you have some data that can help in answering some questions raised in this presentation, Let's Talk

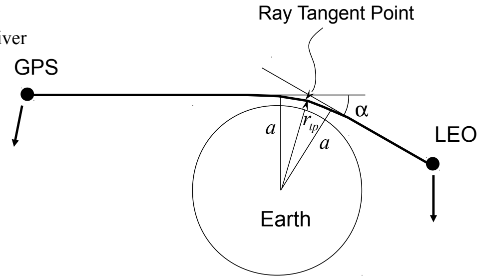
Supplement Ground based data with LEO satellite data

Zama Katamzi (South African National Space Agency)
Endawoke Yizengaw (Institute of Scientific Research, Boston College, USA)

Radio Occultation. RO: Credit to ....

Radio Occultation Observation

During a GPS occultation a GPS receiver in LEO 'sees' the GPS SV set or rise behind the Earth's limb while the signal slices through the atmosphere.



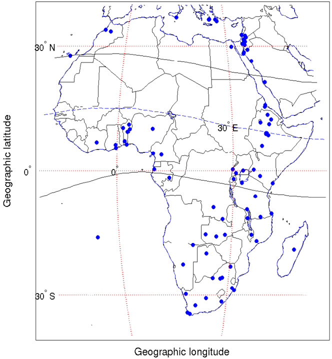
The GPS receiver in LEO observes the change of the delay of the signal between the GPS and the LEO that is related to slowing and bending of the signal path.

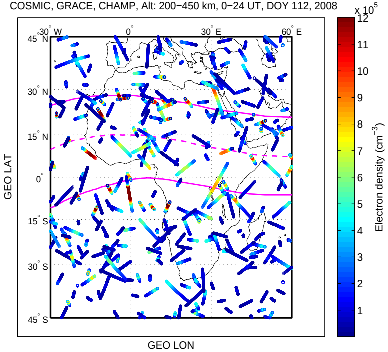
The change of the delay allows for reconstruction of the bending angle α and then the vertical refractivity profile at the ray tangent point

The refractivity allows for reconstruction of the pressure, temperature and humidity in the neutral atmosphere and electron density in the ionosphere

Reference: Kursinski et al., (2000): The GPS Radio Occultation Technique, Terr. Atmos. Ocean. Sci., 11 (1), 53–114

To supplement African GPS and Ionosonde coverage and other data sources





- Four ionosonde stations with continuous data records (South Africa), 1 station over the ocean (Ascension Islands, also African as per John Bosco's allocation.. sorry to the owners)
- Two newly installed ionosondes (Kenya and Ethiopia)
- Two ionosondes with some data (Cote d'Ivoire and Nigeria).

Spatial coverage: Previous studies

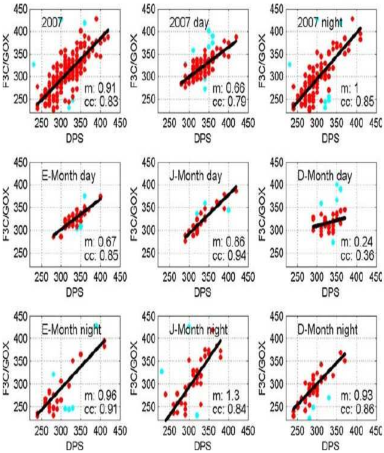
- Satellite passes give little data for direct comparative purposes
- Over any location of interest, there are latitude and longitude considerations:

1. Chu et al., (2010) did a global survey comparing COSMIC and ionospheric parameters using 1^o (latitude/longitude) coverage. Higher hmF2 values were observed for COSMIC data compared to ionosonde data and COSMIC Ne values were systematically smaller.
2. Liu et al., (2011) looked at global features of COSMIC data over mid and low latitudes during solar minimum (2008-2009), and reported complicated seasonal variations of NmF2, hmF2 etc.

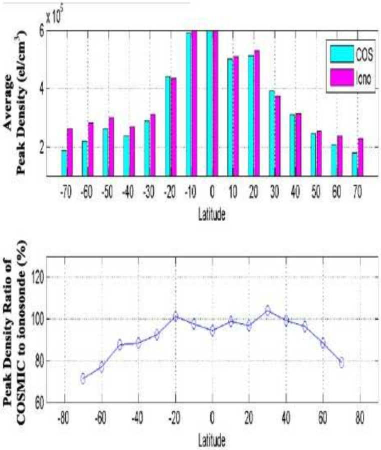
Regional studies

Krankowski et al., (2011) analysed COSMIC Ne and validated it with ionosonde data over Europe, found good agreement between the two data sets using the ionospheric correlation distance of 1000-1500 km

Regional studies ... continued



Liu et al., (2010): Electron density profiles in the equatorial ionosphere observed by the FORMOSAT-3/COSMIC and a digisonde at Jicamarca, GPS Solutions, 14, 75-81: $10^o \times 10^o$ latitude/longitude, 2007



Chu et al., (2010): A global survey of COSMIC ionospheric peak electron density and its height: A comparison with ground-based ionosonde measurements, ASR, 46 431-439: $1^o \times 1^o$ latitude/longitude, July 2006 - Feb 2007

Spatial considerations, what has been done

- Different electron density gradients do not allow uniform spatial choice for validation
- Consider latitudes/longitudes of $10^o \times 10^o$ to $1^o \times 1^o$ in steps of 1^o

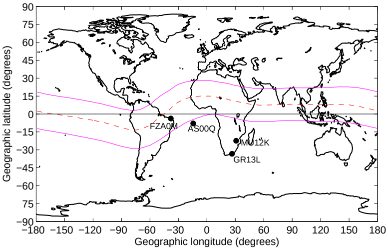
For every latitude/longitude combination find

$$X \approx F_t^i \cap F_t^c$$

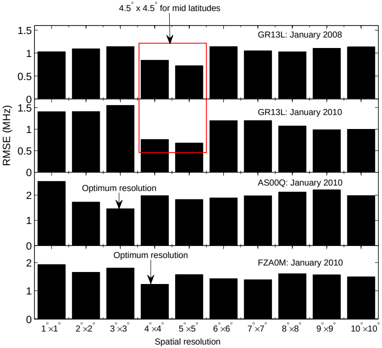
where F_t^i is the ionosonde foF2 at time t and F_t^c is the COSMIC foF2 at time t, and compute root mean square errors, as long as the difference in time for both observations do not exceed the sampling time of the ionosonde data

$$R_c^i = \sqrt{\frac{1}{N}\sum_{j=1}^{N}(F_t^i - F_t^c)^2} \tag{20}$$

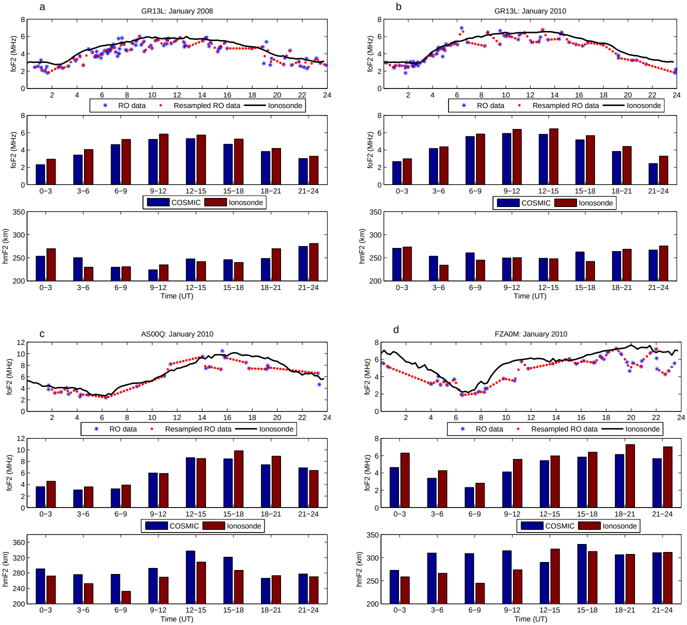
Study locations



(a) A map showing the ionosonde stations used in this study (indicated by solid dots). The dashed line depicts the geomagnetic equator.The equatorial ionisation anomaly region is represented by solid lines at ≈ ±15° latitudes from the geomagnetic equator.

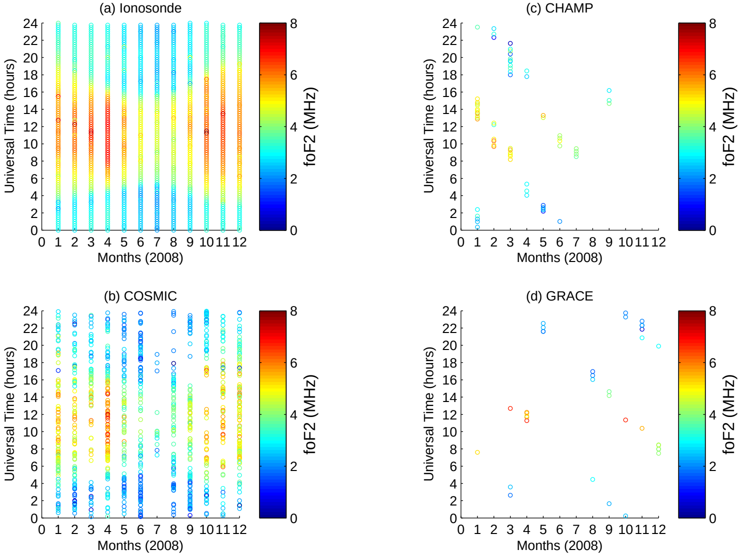


Occultation and ionosonde data comparison

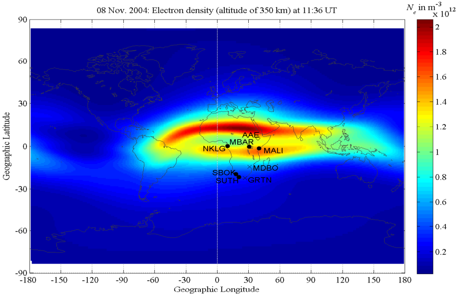


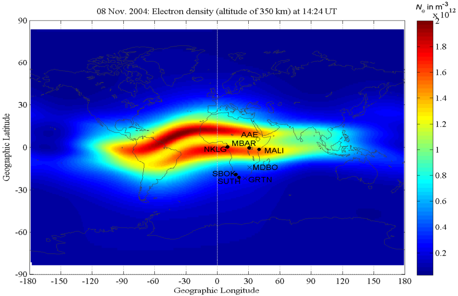
Statistical results: GR13L ($33.3^oS, 26.5^oE$), 2008

Based on monthly foF2 values from both ionosonde and RO



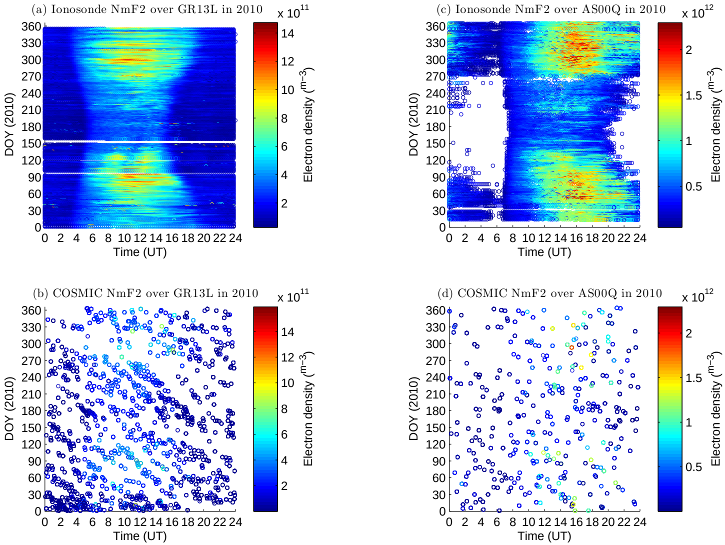
Varying electron density gradients





Habarulema et al., (2013), Journal of Atmospheric and Solar Terrestrial Physics

Occultation and Ionosonde data: GR13L (33.3^oS,26.5^oE) and AS00Q (7.9^oS,14.4^oW)



Summary

- Spatial coverage differs with respect to region. Easily detectable over mid-latitudes than low latitudes
- COSMIC electron densities are systematically smaller than ionosonde values. Peak height COSMIC hmF2 is higher than ionosonde hmF2
- Performing a direct comparison is a difficult task and so averages are used to derive conclusions

Based on statistical analysis, it is found that $4.5^o \times 4.5^o$, $3^o \times 3^o$ and $4^o \times 4^o$ are the approximate suitable spatial resolutions in both latitude and longitude space over an ionosonde station for effective comparisons for mid-latitude, low-latitude and equatorial regions respectively.

Conclusions

- Discussions about the attempts towards modelling ionospheric parameters over the African sector
- Modelling approach is successful for quiet conditions and during negative ionospheric effects
- Difficult to model positive storm effects
- Characterised possible sources for positive storm effects– Large scale TIDs
- Investigated methods for supplementing GNSS and ionosonde infrastructure with Radio Occultation data

Conclusions

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Final remark

There are many research problems to keep us busy for the rest of our lives due to this business of trying to solve a problem and you introduce additional problems

Thank You, Murakoze, **Merci**, Asante, Mwebale

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References/Acknowledgements

1. Krankowski et al., (2011): Ionospheric electron density observed by FORMOSAT-3/COSMIC over the European region and validated by ionosonde data: J. Geod, 85, 949-964.
2. Liu et al., (2011): Features of the middle- and low-latitude ionosphere during solar minimum as revealed from COSMIC radio occultation measurements, JGR, A09307, doi:10.1029/2011/JA016691.
3. Yue et al., (2013): GNSS radio occultation (RO) derived electron density quality in high latitude and polar region: NCAR-TIEGCM simulation and real data evaluation, JASTP, 98, 39-49

- *Radio Occultation data was downloaded from ftp://cdaac-ftp.cosmic.ucar.edu/cosmic/level2/ionPrf/*
- *FZA0M and AS00Q data was downloaded from http://spidr.ngdc.noaa.gov*