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Analysis of ionospheric Total Electron Content variability determined from Global Navigation Satellite System data

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ABSTRACT

Free electrons refract signals transmitted from satellites mainly during their trans-ionospheric propagation. The side-effect is the measured path length travelled by a signal is about five to fifteen meters longer than the actual path covered. Moreover, magnitudes of signal delays are directly proportional to the Total Electron Content (TEC). TEC is an ionospheric parameter indicating the total amount of electrons along a signal path between satellites and ground based receivers. This study was conducted because the TEC-induced ionospheric delay is the main error source in single frequency receivers. Hence, this study involved the extraction of TEC values from GNSS data with the Global Positioning System (GPS) TEC software to observe diurnal and seasonal variations of GNSS-TEC. Additionally, the study compared TEC plots of Windhoek (22.5741ºS; 17.0894ºE), Hermanus (South Africa, -34.42463056ºS; 19.22306111ºE), and Dakar (Senegal, 14.720903ºN; -17.439503ºW) to validate whether the ionospheric delay varies in accordance with the geographic location or not. Comparisons of observational GNSS-TEC and IRI-TEC derived from the IRI model were made to determine the accuracy of the IRI-model in the southern hemisphere. GNSS data were derived from a dual-frequency receiver installed at Windhoek (22.5741ºS; 17.0894ºE), Namibia. Results show that maximum TEC was prevalent in spring while minimum TEC generally occurred throughout winter. Moreover, results revealed that the International Reference Ionosphere (IRI) model overestimated GNSS-TEC in winter but underestimated during summer, autumn and spring.

1. Introduction

Receivers find their positions by means of triangulation, a technique that requires computing the distance to the satellite by multiplying the signal travel time by the speed of light. However, signals do not exactly travel at the speed of light because the atmosphere is not a vacuum, they pass through various atmospheric layers with different indices of refraction during their propagation and each layer refracts these signals. The ionosphere is the atmospheric layer that significantly delays GNSS signals causing errors in GNSS positioning applications and ionospheric refraction of GNSS signals is in direct proportion to TEC (Tariku, 2015). TEC is an ionospheric parameter indicating the total amount of electrons along a signal path between satellites and ground based receivers. It varies in accordance with diurnal variations, seasonal variations, solar activity, geomagnetic activity and the geographic location and it is measured in TEC units (TECU).

$$TECU = \frac{10^{16} el}{m^2} \quad \text{.................................Equation 1}$$

where el stands for electronics and m stands for meters.

Since the ionospheric delay is proportional to TEC this study required the determination of TEC from GNSS data to study its diurnal, seasonal and annual variations and determine the season with maximum and minimum TEC in Windhoek. The study also comprises a brief review of the GNSS constellation which refers to satellite navigation systems such as the American Global Positioning System (GPS), the Russian Global Orbiting Navigation Satellite System (GLONASS), the Chinese Beidou and Galileo for the European Union (Evan, 2016). The GPS-TEC software processed GNSS data to answer the following research questions:

- Is GNSS-TEC proportional to the ionospheric delay estimated by the Global Positioning System Analysis and Positioning Software (GAPS) software?
- How does observational GNSS-TEC relate to modelled IRI-TEC?
- Which hour experiences the maximal diurnal variation of TEC in Windhoek?
- How does TEC varies in accordance with the geographic location of GNSS receivers by comparing TEC of Windhoek (22.5741°S; 17.0894°E), Hermanus (South Africa, -34.42463056°S; 19.22306111°E), and Dakar (Senegal, 14.720903°N; -17.439503°W)?

2. Materials and Methods

A feasibility study was first conducted to determine the viability of the study. After that a logical framework was compiled, comprising project aims, objectives, function list, hardware and software partitioning, dollar-ware and the envisioned project timeline. Several literature were reviewed to understand the GNSS constellation, GNSS applications and the ionosphere. GNSS data were entered as input files in the GPS-TEC analysis application software for data processing. Figure 1 below is a graphical illustration of the steps taken to reach the objectives of this study.

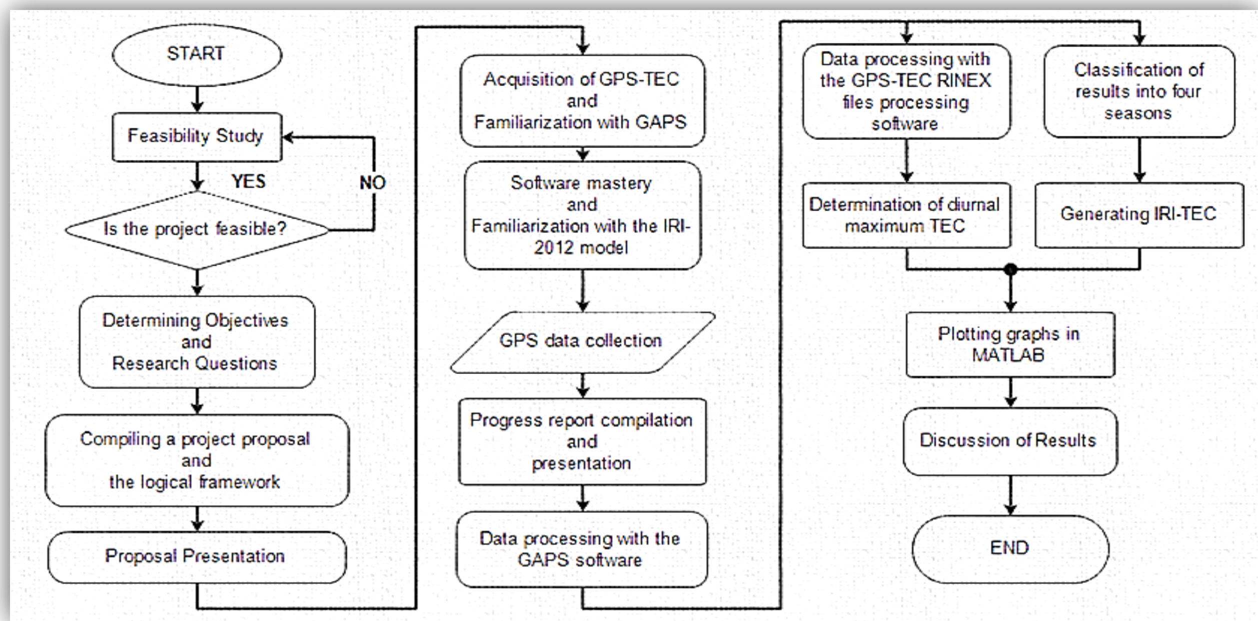


Figure 1. Project flowchart

Two GNSS software, namely the GPS-TEC software and the GPS Analysis and Positioning Software (GAPS) are used to process data. GNSS data were collected with the dual-frequency receiver of the Windhoek Department of Surveying and Mapping. Observational GNSS data are downloaded from (http://www.sonel.org/spip.php?page=gps&idStation=2481%29). Receiver Independent Exchange (RINEX) files are downloaded from (ftp://cddis.gsfc.nasa.gov/pub/gps/data/daily). GNSS navigation files were downloaded from the

International GPS Service (IGS) website with the GPS-TEC software. Annual GNSS data of 2013 and 2015 were classified into summer, autumn, winter and spring. Summer covers January, February and December while winter comprises June, July and August. Autumn consists of March, April and May while spring contains September, October and November.

3. Results

3.1 The Global Navigation Satellite System

The GNSS is a constellation of satellite systems made up of the American Global Positioning System (GPS), the Russian Global Orbiting Navigation Satellite System (GLONASS), the Chinese Beidou and Galileo for the European Union. Figure 2 below graphically illustrates the GNSS network and the main purpose of these network is to allow compatible receivers to precisely and accurately compute position, perform navigation and synchronize their times (50 GPS Basics, 2001).

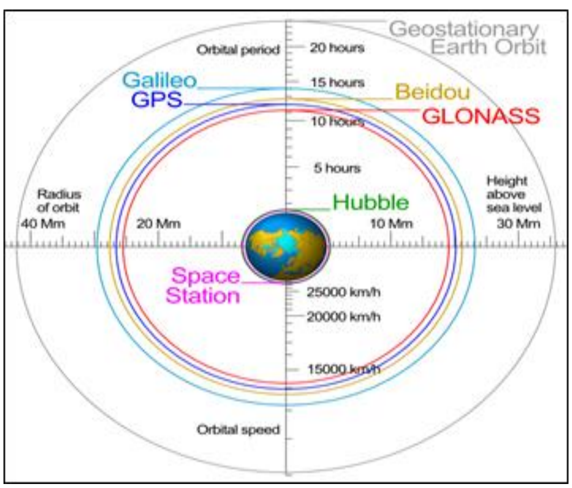


Figure 2. The GNSS constellation (Evan, 2016)

According to Figure 3 below each GNSS has three segments, namely the space segment, control segment and the user segment. The user section displayed in Figure 3 below includes ground based receivers in the form of cellpones and car GPS antennas, the space section has space bound satellites while the control segment comprises sophisticated stations tasked with tracking satellites, correcting and uploading broadcast ephemerides (satellite orbital data) into satellites and monitoring satellite health (Global Navigation Satellite System (GNSS), 2006).

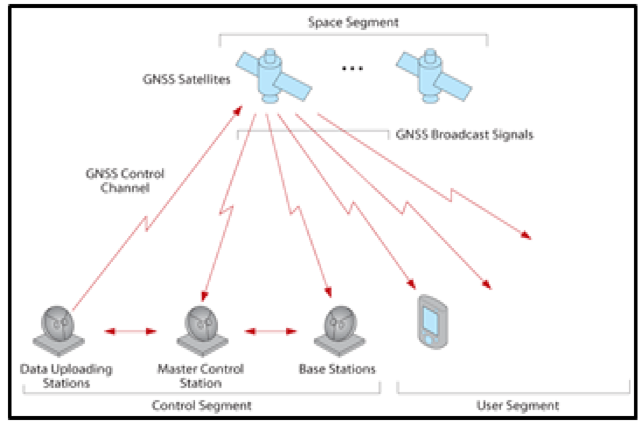


Figure 3. The three GNSS segments (An Introduction to GNSS , 2016)

3.2 Interpretation of TEC plots

According to Figure 4 TEC is around 30-55 TECU in summer and roughly 45-54 TECU in autumn, but in May (last month before winter), TEC drops to the 28-30 TECU range as winter emerges. In autumn TEC normally peaks in March and through summer it peaks in December.

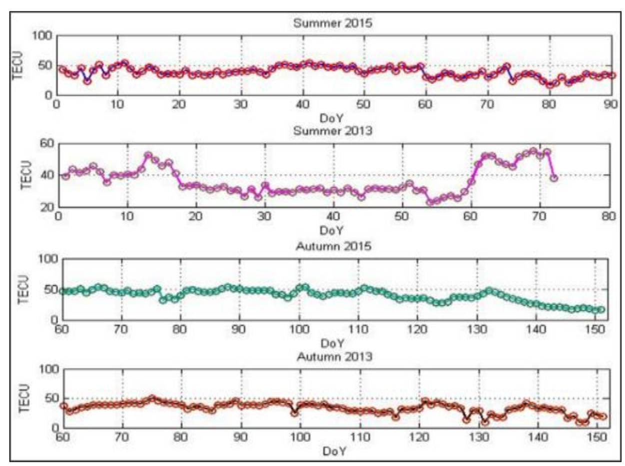


Figure 4. GNSS-TEC in summer and autumn

Figure 5 shows that TEC is continuously around 17-25 TECU in winter and approximately 45-70 TECU in spring, but winter-like TEC is prevalent in September as it is similarly about 17-25 TECU. Additionally, results show that 67.9 TECU experienced in November 2015 is the maximum GNSS-TEC of Windhoek and 2.9 TECU in June 2015 is the minimum.

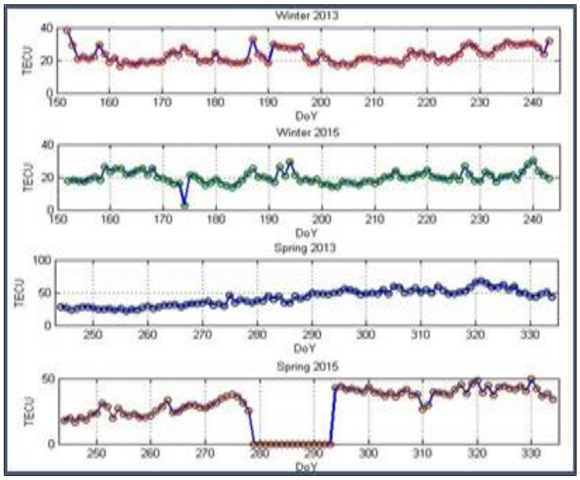


Figure 5. GNSS-TEC in winter and spring

iii. **TEC Plots and Analysis**

Comparisons of ionospheric delay plots and GNSS-TEC plots confirm the validity of Equation 2 which shows the theoretical direct relation between the ionospheric delay (Δ_i^{iono}) and TEC and the inverse proportionality between the delay and the square of the carrier frequency (f_1^2) of the GNSS signal.

$\Delta_i^{iono} = 40.3\frac{TEC}{f_1^2}$……………………………….. Equation 2

For instance, maximum delay of Figure 6 below and maximum TEC in Figure 7 congruently occur at around 1100-1400 UT while both the minimum delay and minimum TEC correspondingly occur around 0000-0500 UT.

Figure 6. Diurnal ionospheric delay

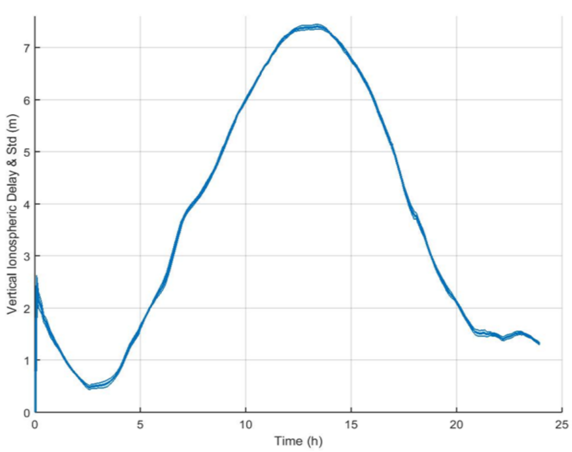
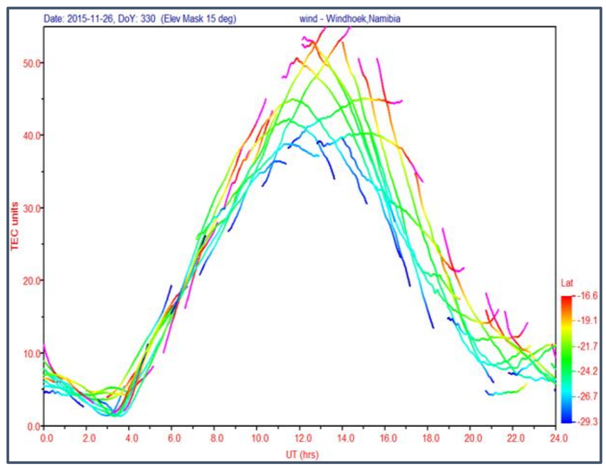


Figure 7. Diurnal GNSS-TEC



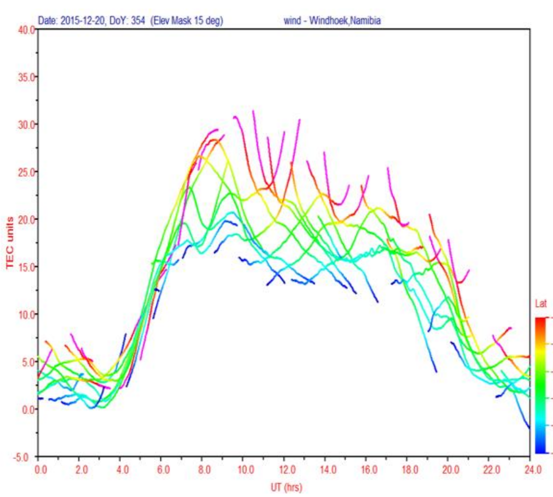


Figure 8. Diurnal GNSS-TEC

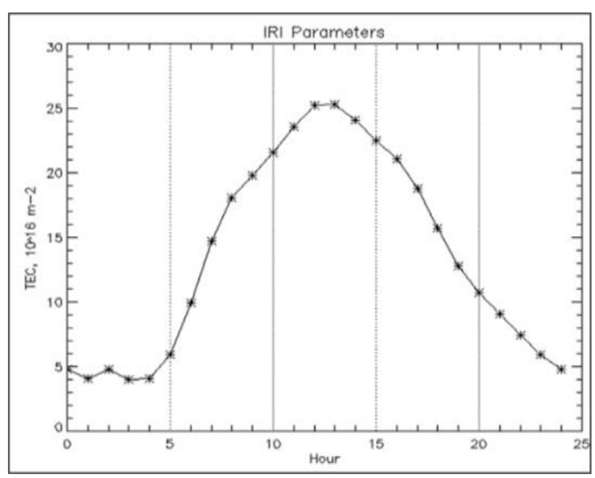


Figure 9. Diurnal IRI-TEC

Results below show how observational GNSS-TEC relates to modelled IRI-TEC. According to Figure 9 the IRI-2012 model accurately predicts GNSS-TEC in Figure 8 during predawn hours but its accuracy deteriorates after sunrise around 11OO-16OO UT.

According to Figure 10 and Figure 11, the IRI-2012 model overestimates GNSS-TEC in winter (153-244 date of the year (DoY)) till early spring (245-274 DoY) and underestimates GNSS-TEC in summer, autumn and during late spring. Both minimum GNSS-TEC and IRI-TEC generally occur in winter (153-244 DoY). The greatest discrepancy occurs in spring 2013 (274-334 DoY) where the maximum GNSS-TEC is 67.9 TECU while the maximum IRI-TEC is 40.1 TECU.

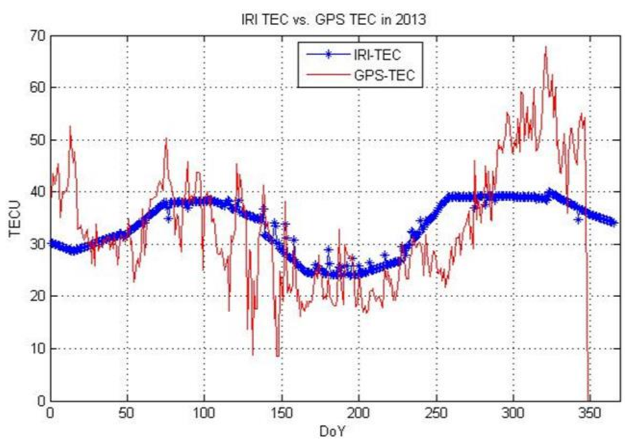


Figure 10. Annual GNSS-TEC against IRI-TEC (2013)

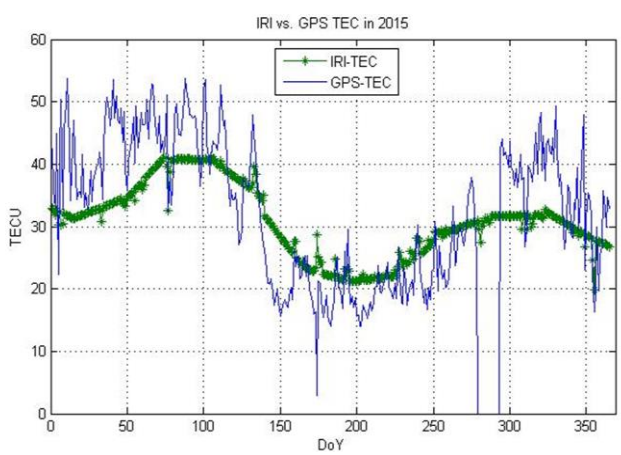


Figure 11. Annual GNSS-TEC versus IRI-TEC (2015)

Equation 3 is the percentage deviation of TEC and if IRI-TEC (I_{TEC}) exceeds GNSS-TEC (G_{TEC}) the percentage deviation turns negative.

$\frac{G_{TEC}-I_{TEC}}{G_{TEC}} \times 100\%$......................................Equation 3

Figure 12 and Figure 13 illustrate the variation of maximum diurnal TEC of January, March, June and November at Hermanus (HERM), Windhoek (WIND) and Dakar (DAKR) 2013.

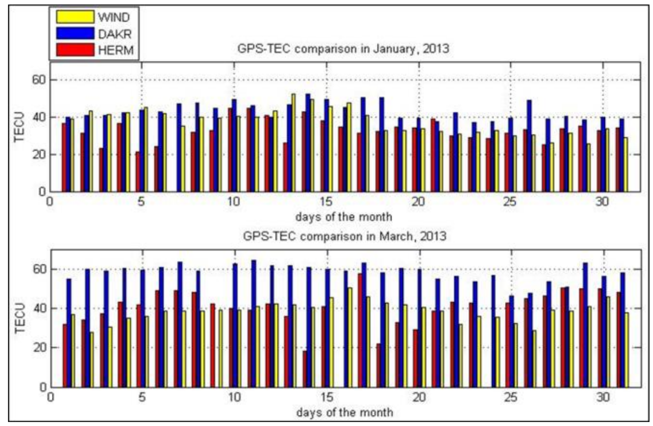


Figure12. Monthly comparisons GNSS-TEC at DAKR, WIND and HERM (2013)

During the abovementioned four months, Dakar (14.720903^{o} -17.439503^{o}W) generally has maximum TEC. Also, Windhoek has higher TEC than Hermanus. Windhoek is at a mid-latitude region and Hermanus is at a low-latitude region. Dakar has the highest TEC (78.2 TECU) because it is closer to the Equator (0^{o}) in comparison to Windhoek (-22.5741^{o}S; 17.0894^{o}E) and Hermanus (-34.42463056^{o}S; 19.22306111^{o}E).

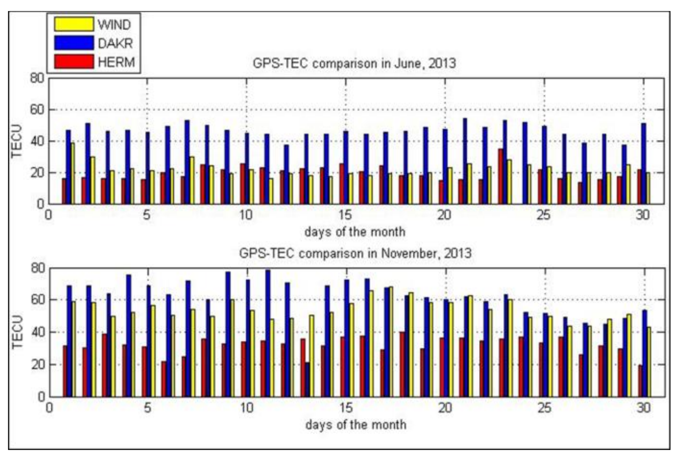


Figure13. Monthly comparisons GNSS-TEC at DAKR, WIND and HERM (2013)

Discussions

Comparing ionospheric delay plots of the GAPS software and GNSS-TEC plots of the GPS-TEC software reveals that the delay in GNSS measurements is proportional to GNSS-TEC. Minimal ionospheric delays generally occur between 0000 UT (midnight) and 0500 UT (pre-sunrise). This period is typically linked with few free electrons in the ionosphere due to the recombination process. Recombination involves cations and free electrons re-joining to form neutralized atoms and molecules (Anderson & Fuller-Rowell, 1999). Fewer electrons mean a GNSS signal undergoes less refraction between the 0000 UT and 0500 UT time period. The IRI-2012 model's diurnal prediction of GNSS-TEC is accurate during predawn hours and exactly before midnight. After sunrise accuracy declines hence it starts underestimating GNSS-TEC and this could be due to an increase in ionisation.

Both maximum GNSS-TEC and IRI-TEC occur at midday hours (1000-1300 UT). The IRI-2012 model overestimates GNSS-TEC in winter. This is validated by a negative percentage deviation of TEC generated with Equation 3. A negative deviation implies that IRI-TEC is greater than GNSS-TEC. However, this is invalid in summer, autumn and spring as TEC deviation is dominantly positive. Minimum GNSS-TEC and IRI-TEC generally occurs in winter. The model consistently approximates GNSS-TEC, but discrepancies between observational and modelled results are significant. A study conducted by (Norsuzila, Mardina, & Ismail, 2010) reveals that discrepancies are due to insufficient data on the topside height of the ionosphere in addition to random day-to-day variations of TEC that are not catered for by the model.

GNSS-TEC of 2015 is evidently greater than GNSS-TEC of 2013 in summer, autumn and winter. Spring of 2013 has higher GNSS-TEC than spring of 2015. TEC is persistently below 40 TECU in winters of 2013 and 2015. In detail only seven days have beyond 30 TECU in winter of 2013. August has maximum overall TEC followed by June and lastly July. In summer TEC is above 30 TECU and normally reaches the 50-54 TECU range. In 2013 February has overall minimum TEC while December has overall maximum TEC, but in 2015 February has maximum TEC and December has minimum TEC. In autumn TEC is above 30 TECU and usually reaches the 45-50 TECU range. Minimum TEC is prevalent in May while maximum TEC is predominant in March. September has minimum TEC in spring while November has maximum TEC. Maximal TEC occurs around 1200 UT and this is the period when the sun is more direct (Norsuzila, Mardina, & Ismail, 2010).

Dakar (14.720903^{o}N; -17.439503^{o}W) has higher TEC than Windhoek (-22.5741^{o}S; 17.0894^{o}E) and Hermanus (-34.42463056^{o}S; 19.22306111^{o}E) as shown in Figure 14 due to its nearness to the Equator. Solar radiation at the Equator is higher; thus, ionization is correspondingly intense. TEC varies in accordance with geographic latitude of GNSS receivers and decreased as the distance from the Equator increased. Windhoek has higher TEC than Hermanus because Windhoek is a mid-latitude region and Hermanus is a low-latitude region. Overall minimum TEC occurs in June at both three stations. November has maximum TEC in comparison to the other three months. At Dakar TEC is around 60-80 TECU in November and average monthly TEC is 61.81333 TECU.

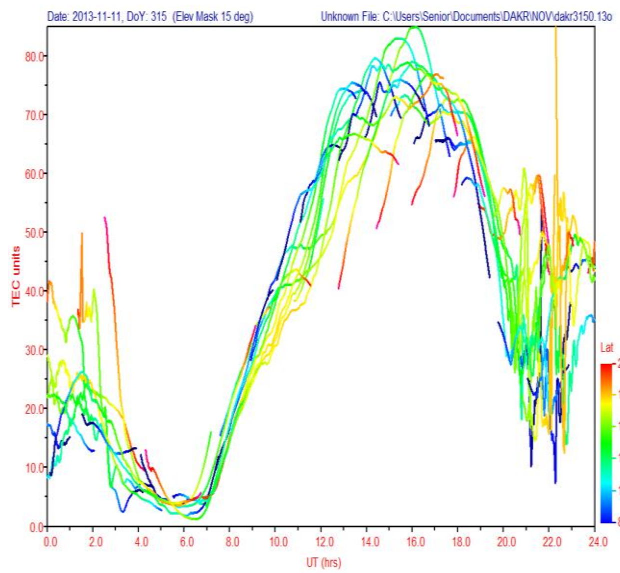


Figure 14. Maximal diurnal TEC variations at Dakar (11 November 2013)

At Windhoek TEC is around 45-67 TECU. Average monthly TEC is 53.98667 TECU in November while maximum TEC is 67.4 TECU. Hermanus has a monthly average TEC of 32.53 TECU in November. Minimum TEC occurs at around 0600 - 0700 UT at Dakar, but occurs at around 0400-0600 UT at Hermanus and Windhoek. Maximum TEC occurs around 1600-1800 UT at Dakar, but at Hermanus and Windhoek it occurs at 1200 UT.

Conclusion

Seasonal and diurnal variations of an ionospheric parameter designated "TEC" over Windhoek in 2013 and 2015 were monitored. Results revealed that the ionospheric delay conforms to the random variations of TEC but the tropospheric delay does not. Minimum ionospheric delays occur between midnight and pre-sunrise. The IRI model is more accurate during predawn hours, a period with less TEC due to the recombination process. According to GNSS-TEC and IRI-TEC results, maximal TEC occurs at midday hours (1000-1300 UT). The IRI model overestimates GNSS-TEC in winter and underestimates in summer, autumn and spring. Winter generally had overall minimum GNSS and IRI-TEC. The discrepancy between IRI-TEC and GNSS-TEC is due to insufficient data on the topside height of the ionosphere in addition to day-to-day variations of TEC that are not catered for by the IRI model. Solar radiation is maximal at the Equator; hence, Dakar (Senegal) has higher TEC than Windhoek and Hermanus (South Africa) because it is closer to the Equator. Currently, the number and distribution of active GNSS receivers in Namibia are inadequate to give a good representation of the variability of the ionosphere over Namibia. Increasing the number of stations to give a more representative distribution, will improve this situation.

Acknowledgements

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