GPS POSITIONING IMPROVEMENT BY MITIGATING THE IONOSPHERIC HORIZONTAL GRADIENT

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I dedicate this entire work to my beloved parents, Sa'at & Adidah,
my sisters, Narisa & Nasrin,
my nephew, Naseem,
and all my friends
for their support and encouragement that has
constantly been a part of this journey.

In the end, it is the journey that matters along with prayer and food!

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ABSTRACT

A 3D ionospheric model was developed using TC3D and IRI to enhance the effect of the ionosphere to the GPS signals. Four comparisons have been done to see the effect of the DGPS positioning such as baselines length (short and long), low and high solar activity, range measurement from three and eight satellites and two different duration times (one and three hours). Some improvements can be seen after the corrections and it was a noticeable positioning improvement at the user location over the equatorial region. Improvement in the final positioning error can be found for all cases; with and without ionospheric corrections. From the results, positioning improvement has been achieved where only 26% of percentage error is from short baseline, 27% of percentage error from low solar activity, percentage error from 24% of 8 satellites and 40% of 3 hours period of time. It shows that it is important to consider criteria such as shorter baseline with more satellites viewing for longer duration of time (in hour) during low solar activity to achieve the improvement in the positioning. The effect of the ionospheric horizontal gradient which is more noticeable in the equatorial region has been resolved and will be very beneficial to improve the positioning of the user location, especially in applications such as surveying, geophysics, navigation and aviation.

ABSTRAK

Model 3D ionosfera telah dibangunkan dengan menggunakan TC3D dan IRI bagi meningkatkan kesan ionosfera ke atas isyarat GPS. Empat perbandingan telah dilaksanakan bagi melihat kesan daripada kedudukan DGPS seperti ukuran garis dasar (pendek dan panjang), aktiviti solar tinggi dan rendah, pengukuran daripada tiga dan lapan buah satelit dan dua tempoh masa yang berbeza (satu dan tiga jam). Beberapa penambahbaikan dapat dilihat selepas pembetulan tersebut dan ini merupakan peningkatan ketara kedudukan di lokasi pengguna rantau Khatulistiwa. Peningkatan dalam ralat kedudukan terakhir boleh didapati untuk semua kes; dengan dan tanpa pembetulan ionosfera. Daripada keputusan, kedudukan peningkatan yang telah dicapai di mana hanya 26% daripada ralat peratusan dari garis dasar pendek, 27% daripada ralat peratusan daripada aktiviti solar rendah, ralat peratusan daripada 24% daripada 8 satelit dan 40% daripada tempoh masa 3 jam telah ditunjukkan. Ia menunjukkan adalah penting untuk mempertimbangkan kriteria seperti garis dasar yang lebih pendek dengan lebih satelit bagi jangka masa yang lebih lama (dalam jam) semasa aktiviti solar rendah bagi mencapai peningkatan dalam penentududukan. Kesan kecerunan mendatar ionosfera yang lebih ketara di kawasan khatulistiwa dapat diselesaikan dan akan menjadi sangat bermanfaat untuk meningkatkan kedudukan lokasi pengguna, terutamanya dalam aplikasi seperti pengukuran, geofizik, navigasi dan penerbangan.

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LIST OF ABBREVIATIONS

CORS	Continuously Operating Reference Station
COSPAR	Committee on Space Research
CS	Control Segment
DGPS	Differential Global Positioning System
EUV	Extreme Ultraviolet
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HF	High Frequency
IRI	International Reference Ionosphere
ISK	IskandarNet Station
K_p	Geomagnetic K-index
L_1	Prime GPS Carrier Frequency (1557.42 MHz)
L_2	Secondary GPS Carrier Frequency (1227.6 MHz)
LF	Low Frequency
LT	Local Time
MEO	Medium Earth Orbit
MF	Medium Frequency
NASA	National Aeronautics and Space Administration
N_e	Electron Density
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
NTUS	Nanyang Technological University Singapore
PDOP	Positioning Dilution Of Precision
RMS	Root Mean Square
SPS	Standard Positioning Service
SS	Space Segment
SSE	Sum of Squared Error

sTEC	Slant Total Electron Content
SV	Space Vehicles
TBC	Trimble Business Center
TC3D	Table Curve 3 Dimension
TEC	Total Electron Content
TECU	Total Electron Content Unit
URSI	International Union of Radio Science
UV	Ultraviolet
VHF	Very High Frequency
VLF	Very Low Frequency
WOC	without correction

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CHAPTER 1

INTRODUCTION

1.1 Project background

Ionosphere is one of the atmospheric layers that play an important role in radio communication. The ionospheric layer is formed by free electrons or sometimes termed as electron density concentration varies with height or distance from the Earth's surface, latitude, time of day, season, and amount of solar activity [1]. For high frequency (HF) propagation (3 to 30MHz), ionospheric layer acts as a conductive region which reflects the radio wave signals at specific frequencies to any radio receiver station on the Earth. However, for transionospheric propagation, it acts as a dispersive medium for some radio signals (in the range of 30MHz to 3GHz). Those radio signals' speed of propagation or termed as group path will be delayed.

Ionosphere is prone to significant disturbances, which get considerably worst during periods of high solar activity [2]. Due to that, and as was mentioned above, the radio signals that propagates through the ionosphere suffers increment of group path delay which is proportional to the content of free electrons. The scenario is worst for the radio signals that propagate over the equatorial region. The fact that the ionosphere is formed by the radiation from the Sun suggests that this mechanism results in variations in the ionosphere with time of day, season, solar cycle and position on the Earth surface. The travel time of Global Positioning System, (GPS) satellite signals can be altered by atmospheric effects; when a GPS signal passes through the ionosphere it is refracted, causing the speed of the signal to be different from the speed of a GPS signal in space. Sunspot activity also causes interference with GPS signals [3].

The GPS signals will be delayed as they propagate through the ionosphere. The ionosphere will introduce a significant amount of added group delay which will affect the final GPS positioning, if the ionospheric error is not corrected. An example of large ionosphere gradients that could cause the significant GPS user errors have been observed [4]. A number of studies have been done and is still continuing to mitigate the ionospheric horizontal gradient by using variety of methods in order to improve the final user positioning [5]–[8]. For any GPS applications over the equatorial region (i.e. navigation, surveying, mapping, mining, agriculture and automatic aircraft landing), the ionospheric error and the horizontal gradient effect need to be corrected in order to determine the most accurate or precise GPS final positioning. Many researches also have investigated the GPS positioning improvement using different methods for different range of conditions [9]–[11].

In this research, first of all, the effect of the ionosphere over the equatorial region (e.g. Malaysia) has been investigated. Then, three dimensional analytical mathematical models have been developed to represent the actual formation of the ionosphere over the equatorial region. The existing ionospheric online-database such as International Reference Ionosphere (IRI) [12], which contains the value of electron density at various location and time, was used to do the analytical modeling. After that, the characteristics of the GPS signals as they propagate through the ionosphere have been determined. By doing so, the effect of the ionosphere to GPS positioning has been obtained. To further the research work, GPS positioning improvement were done by mitigating the ionosphere horizontal gradient using Trimble Business Center (TBC) software.

1.2 Problem statement

Over the equatorial region, the formation of the ionosphere introduces greater ionospheric horizontal gradient which could give greater positioning error for a user station in a GPS system. The ionospheric horizontal gradient is the variation of electron density with latitude and longitude which can cause the azimuthally deviation of the GPS ray path. The electron density in the ionosphere will cause greater refraction to the GPS signals as it propagates through it. Due to the refraction, the final GPS positioning is not accurate. GPS positioning accuracies are affected by different error sources. Therefore, TBC software will be used in order to mitigate the effect of the ionosphere to GPS signals and a 3 dimensional (3D) analytical mathematical model will be developed using IRI.

1.3 Research objectives

The objectives of this research:

1. To determine the ionospheric effect over the equatorial region.
2. To develop the 3D analytical mathematical model.
3. To analyze and mitigate the ionosphere horizontal gradient using TBC software for positioning.

1.4 Scope of the project

1. The region of this study is focused only from the middle to the southern region of Peninsular Malaysia
2. Data was taken from stations of Nanyang Technology University Singapore (NTUS) (1.34°N, 103.7°E), Universiti Kebangsaan Malaysia (UKM) (9.92°N, 101.7°E) and ISKANDARnet (ISK) (1.56°N, 103.6°E) on June 2009 (low solar activity) and August 2012 (high solar activity).

1.5 Thesis outline

In general, this thesis consists of five chapters. Each chapter will discuss on different issues related to the project.

The first chapter describes an overview of the project background, problem statement, research objectives and scope of the study to carry out the project.

Chapter two focuses on the review from previous studies that was made which was helpful to gain knowledge and to understand the project better. It presents some general review of the ionosphere and basic principles on GPS and its characteristic.

Chapter three elaborates the methodology of the research. This project requires a lot of simulations such as using IRI to obtain electron density, Table Curve 3D (TC3D) for calculation and viewing the 3D graph, and TBC software to improve GPS positioning.

Chapter four contains the details of data that was analyzed. It also contains the discussion from this research. Comparisons are made to determine the best result.

Lastly, chapter five includes the conclusions and recommendations that can be done in the future related to this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Ionosphere

The Earth's atmosphere is a thin layer of gases that surrounds the Earth. It composed of 78% of nitrogen, 21% of oxygen and 1% of other gases such as argon and carbon dioxide [13]. This thin gaseous layer insulates the Earth from extreme temperatures; keeps heat inside the atmosphere and also blocks the Earth from the Sun's incoming ultraviolet radiation. The ionosphere, which is found from the altitude of about 60km to 700km, contains up to four layers of free electrons which can enable long-distance radio communication [14]. The GPS signals that are propagated through the atmosphere are affected by several conditions such as variation at different altitudes (height from the surface of Earth), geographical location, diurnal and seasonal changes, and also due to the changes in the Sun's solar activity. The Earth's atmosphere consists of a few layers as can be seen in Figure 2.1.

Ionosphere was formed when extreme ultraviolet (EUV) light from the Sun strips the electrons from the neutral atoms of the Earth atmosphere [15]. This neutral atom known as positive ion when it has lost negative charged electron. This process is known as photoionization [15]. In contrast, recombination is the reverse of photoionization [15]. The rate at which ionization occurs depends on the density of atoms in the atmosphere and the intensity of the EUV, which varies with the activity of the Sun [16].

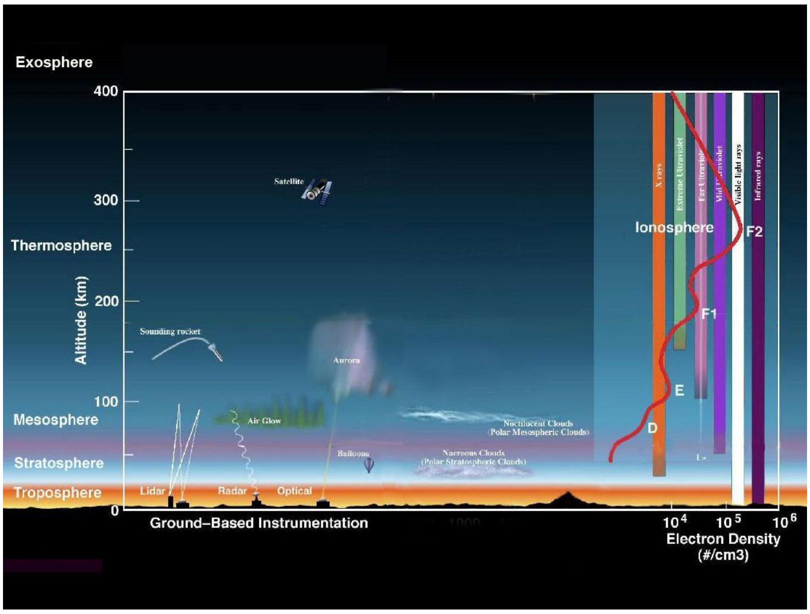

Figure 2.1: Earth’s atmospheric layer [17]

During late afternoon and early evening hours, the rate of recombination exceeds the rate of ionization. Due to this, the density of the ionized layers normally begins to decrease in the D, E and F_1 layers at this time. However, the F_2 layer acts differently. The electron density in the F_2 layer reaches its lowest value just before dawn [18]. Then, once the Sun rises, photoionization takes place which causing the content of electron density to increase again in the F_2 layer. That is the reason for the ionosphere can still be used at night time for HF or ionospheric reflected radio wave propagation. Other than recombination, the protonosphere also plays a role here. The protonosphere acts like a reservoir as there is no plasma production in the protonosphere [19]. It takes plasma from the ionosphere by day, stores it in a loss-free environment and returns it to the ionosphere at night, which helps to maintain the F layer during night time.

2.2 Structures of Ionosphere

The ionosphere is composed of D, E and F layers, named in the order of increasing height as in Figure 2.2. During day time, the radiation of the sun is high on the local atmosphere. At this time, all the layers will exist. At night time or when there is no radiation, the ions and electrons will recombine (recombination process). Only the F_2 layer will be seen since the other three layers (D, E and F_1) almost completely disappear due to the recombination process. The ionosphere is composed of the D, E, F_1 and F_2 regions, named in order of increasing height.

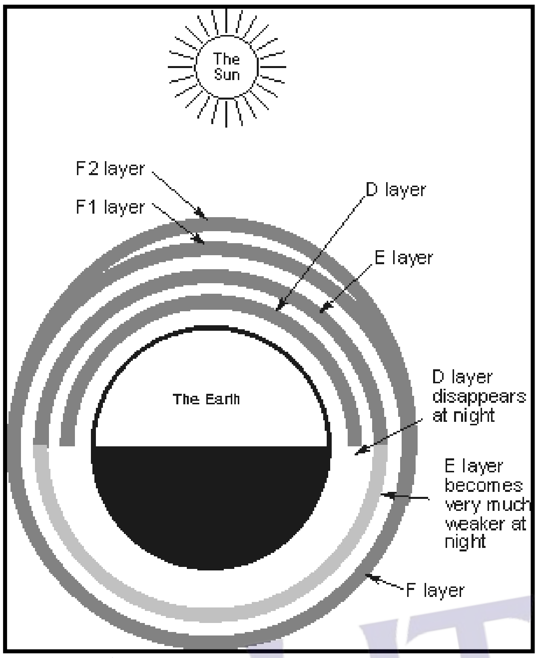

Figure 2.2: View of the layers in the ionosphere over the period of a day [20]

2.2.1 D region (60 to 90 km)

The D region is the bottom layer of the ionosphere that affects radio communication signals to any degree. It is only presents during the day to an extent that affects radio waves noticeably. It mainly has absorbing or attenuating radio communications signals particularly in the LF and MF portions of the radio spectrum, reducing with frequency. At night it has little effect on most radio communication signals although there is still a sufficient level of ionisation for it to refract VLF signals.

2.2.2 E region (100 to 125 km)

Instead of attenuating radio communication signals this layer chiefly refracts them, often to a degree where they are returned to Earth. As such they appear to have been reflected by this layer. However this layer still acts as an attenuator to a certain degree. Like the D region, the level of ionisation falls relatively quickly after dark as the electrons and ions re-combine and it virtually disappears at night. However the residual night time ionisation in the lower part of the E region causes some attenuation of signals in the lower portions of the HF part of the radio communications spectrum.

2.2.3 F region (140 to 500 km)

This is the most important layer of the ionosphere for HF and transionospheric radio wave propagation. It exists from an altitude of about 140 km to 400km and sometimes up to 500 km. During daytime, the F layer will split into two layers; termed as the F_1 and F_2 layers. The F_1 layer is in the altitude range from 130 to 210 km whereas the F_2 layer is from 210 to 400 km; sometimes up to 500 km. It also has been found that, at mid latitudes, the F_2 layer has a higher electron concentration during day time in winter than in summer. This unexpected behaviour in the F_2 layer is called the mid-latitudes seasonal anomaly. Due to their larger electron density, the F_2 layer, and to some extent the F_1 layer, are the major source of ionospheric induced error for range finding and positioning at GPS frequencies.

2.3 Variation in the Ionosphere

The regular variations in ionosphere often known as daily, seasonal, geographical location, latitude and solar cycle variations. The frequencies available for HF communications and other uses of the ionosphere have the same variations and it is important to the propagation of radio waves. For 24-hour diurnal (night/day) variation, rotation of the Earth on its axis, producing daily ionospheric changes [21]. In seasonal variation, the Earth revolving around the sun; the relative position of the Sun moves from one hemisphere to the other with changes in seasons [21]. Latitudinal variation cause by the variation with solar zenith angle and the curvature of Earth causes a geographical variation in the ionospheric electron concentration [22]. Regular solar cycle variation of sunspot activity has a minimum and maximum level and occurs approximately every 11 years [21] and thus produce solar cycle variation.

2.4 Total Electron Content (TEC)

Total Electron Content (TEC) is an important descriptive quantity for the ionosphere. TEC is the total number of electrons present along a path between two points, with units of electrons per square meter, where 1×10^{16} electrons/m² = 1 TEC unit (TECU) [23]. The ionospheric TEC predictions using dual frequency technique and TEC map using Bernese GPS software (BGS) with PPP technique showed that TEC have similar variations, where the TEC values start to increase gradually from morning and reach its maximum in the early afternoon and decrease just before sunrise [24]. TEC during the day was higher than at night and during the low solar activity. It varies from a pre-dawn minimum to a maximum during the afternoon and then decreases [25]. The low values of TEC are observed in winter and high values observed in equinox [26].

TEC is one of the most important parameters that describe the ionospheric state and structure. Theoretically, different periods of ionospheric physical process can be studied by detecting and analyzing the temporal variations of TEC. TEC can be used to correct the radio wave propagation in the space-based radio communication application like satellite position, navigation and orbit determination, because TEC is closely associated with the time delay of the radio wave.

Computing TEC from GPS data is feasible due to the dispersive nature of the ionosphere, which affects the speed of propagation of the electromagnetic waves transmitted by the GPS satellites on two L-band frequencies (L_1=1575.42 MHz and L_2=1227.60 MHz) as they travel through that region of the atmosphere. The change in satellite-to-receiver signal propagation time due to the ionosphere is directly proportional to the integrated free-electron density along the signal path. GPS pseudorange measurements are increased (the signal is delayed) and the carrier-phase measurements are reduced (the phase is advanced) by the presence of the ionosphere. After forming the linear combination of these measurements on the L_1 and L_2 frequencies, the carrier phase and the pseudorange TEC are obtained.

Slant TEC (sTEC) is a measure of the total electron content of the ionosphere along the ray path from the satellite to the receiver. It can be calculated by using pseudorange measurements as in equation (2.1) below:

$$sTEC = \frac{1}{40.3}\left(\frac{{f_1}^2{f_2}^2}{{f_1}^2-{f_2}^2}\right)(P_2 - P_1) \tag{2.1}$$

Where;

f_1 = 1575.42 MHz (high GPS frequency)

f_2 = 1227.6 MHz (low GPS frequency)

P_1 and P_2 are the pseudoranges measured (in distance unit) in L_1 and L_2, respectively

The fundamental navigation principle is based on the measurement of pseudoranges between the user and four satellites. Ground stations precisely monitor the orbit of every satellite and by measuring the travel time of the signals transmitted from the distance of four satellites between receiver and satellites will yield accurate position, direction and speed. The term of ‘pseudoranges’ is obtained when the fourth observation is essential for solving clock synchronization error between receiver and satellite though three-range measurements are sufficient [27].

2.5 Global Positioning System (GPS)

Global navigation satellite system (GNSS) is a generic reference for any navigation system based on satellites; the system in widespread use today is the United States' global positioning system (GPS) [28]. GPS is now widely available for use by many applications. GPS consists of three segments: the space segment, the control segment, and the user segment [29] as shown in Figure 2.3. Twenty-four satellites (the space segment) in orbit around the Earth send data via radio links that allows aircraft receivers (the user segment) to calculate precise position, altitude, time and speed on a 24-hour, worldwide, all weather basis. The principles of satellite navigation are based on radio wave propagation, precision timing and knowledge of each satellite's position above the Earth; this is all monitored and controlled by a network of stations (the control segment) [28].

The main purpose of the GPS is to determine the position and velocity of a fixed or mobile object, placed over or near the Earth surface, using the signals of the satellites. A GPS receiver calculates its position by precisely timing the radio signals sent by the GPS satellites high above the Earth. The receiver measures the transit time of each message and computes the distance to each satellite [30]. Study showed that the seasonal variation is a major factor for determining the accuracy of GPS

REFERENCES

1. A. Gebremedihn. *Tomographic Imaging Of Ionospheric Electron Density Over Eastern Africa Using Multi-Platform Instrumentations And Model Ionospheric Total Electron Content*. Ph.D. Thesis. Addis Ababa University, Ethiopia. 2013.
2. P. Misra and P. Enge. *Global Positioning System: Signals, Measurements, and Performance*. 2nd ed. Ganga-Jamuna Press. 2011.
3. O. Ørpen. Solar Activity and the Effect on Positioning Systems - The first Examples of Disturbances in Solar Cycle 24. *European Navigation Conference*. London. 2013. pp. 6–11.
4. V. S. Srinivas, A. D. Sarma, A. Supraja Reddy, and D. Krishna Reddy. Investigation of the effect of ionospheric gradients on GPS signals in the context of LAAS. *Progress Electromagnetic Research B*. 2014. vol. 57(57): pp. 191–205.
5. C. S. Fah. Significant of Earth's Magnetic Field and Ionospheric Horizontal Gradient to GPS Signals. *Proceeding of the 2013 IEEE International Conference on Space Science and Communication (IconSpace)*. 2013. no. July. pp. 1–3.
6. K. Nagarajoo. DGPS Positioning Improvement by Utilizing the Ionospheric Horizontal Gradient Factor. *Malaysia Annual Physics Conference.* 2011. vol. 164: pp. 2011–2014.
7. K. Nagarajoo. DGPS positional improvement by mitigating the ionospheric horizontal gradient using GPSurvey. *2011 IEEE International Conference on Space Science and Communication: Towards Exploring the Equatorial Phenomena (IconSpace 2011) - Proceedings*. 2011. pp. 65–68.
8. K. Nagarajoo. DGPS Positional Improvement by Mitigating the Ionospheric Horizontal Gradient and Elevation Angle Effects. *Proceedings of 2010 IEEE*

Asia-Pacific Conference on Applied Electromagnetics (APACE 2010). 2010. no. 0660.

9. K. Nagarajoo. *Improved Ionospheric Correction for Dual Frequency and Differential GPS Positioning Methods*. Ph.D. Thesis. The University of Leeds. 2007.
10. N. Ya'acob, M. Abdullah, and M. Ismail. Ionospheric Modelling : Improving The Accuracy of Differential GPS (dGPS) in Equatorial Regions. *2007 Asia-Pacific Conference on Applied Electromagnetics Proceedings (APACE2007)*. 2007. pp. 0–4.
11. U. Dogan, M. Uludag, and D. O. Demir. *Investigation of GPS positioning accuracy during the seasonal variation*. Elsevier. 2014. vol. 53: pp. 91–100.
12. D. Bilitza (2012). *International Reference Ionosphere (IRI-2007).* National Aeronautics and Space Administration (NASA). Retrived on April 22, 2012, from http://ccmc.gsfc.nasa.gov/modelweb/ionos/iri.html.
13. Z. M. Artinian. *The Atmosphere*. Bridges Ed. Benchmark Education Company. 2010. pp. 15.
14. Stefan. F. Bush. *Smart Grid: Communication-Enabled Intelligence for the Electric Power Grid*. John Wiley & Sons. 2014.
15. Leo F. McNamara. *Radio Amateurs Guide to the Ionosphere*. USA: Krieger Pub Company. 1994.
16. P. K. Subhadra Devi. *Behaviour of ionosphere and its interaction with solar magnetosphere system.* Master Thesis. Mahatma Gandhi University. 2014.
17. National Aeronautics and Space Administration (NASA) (2013). *Earth's Atmospheric Layers.* Retrived on August 20, 2013, from http://www.nasa.gov/images/content/463940main_atmosphere_layers2_full.jpg.
18. U.S. Department of Defense. *Communications-Electronics Fundamentals: Wave Propagation, Transmission Lines, and Antennas*. United States: Department of the Army. 2014.
19. Walter Dieminger, Gerd K. Hartmann, Reinhart Leitinger. *The Upper Atmosphere: Data Analysis and Interpretation*. Springer Science & Business Media. 2011.

20. I. Poole (2012). *The Ionosphere and Radiowave Propagation_Radio-Electronics.com*. Retrived on June 06, 2014, from http://www.radio-electronics.com/info/propagation/ionospheric/ionosphere.php.
21. J. Asgari and A. R. Amiri-Simkooei. Analysis and Prediction of GNSS Estimated Total Electron Contents. *Journal of the Earth & Space Physic*. 2011. vol. 37(1): pp. 11–24.
22. M. M. Amin. *Influence of lightning on electron density variation in the ionosphere using WWLLN lightning data and GPS data*. Ph.D. Thesis. Department of Electrical Engineering, University of Cape Town. 2015.
23. J. A. Klobuchar. *Global Positioning System: Theory and Applications.* American Institute of Aeronautics and Astronautics. pp. 485–516. 1996
24. N. Ya'acob, M. Abdullah, and M. Ismail. *GPS Total Electron Content (TEC) Prediction at Ionosphere Layer over the Equatorial Region*. Trends in Telecommunications Technologies. 2000. pp. 485–508.
25. W. Y. Ng, S. A. Bahari, M. Abdullah, and B. Yatim. Regional Ionosphere Maps over Malaysia during Solar Minimum. *Proceeding of the 2009 International Conference on Space Science and Communication*. October 2009. Port Dickson, Negeri Sembilan. pp. 161–165.
26. R. S. Fayose, R. Babatunde, O. Oladosu, and K. Groves. Variation of Total Electron Content (TEC) and Their Effect on GNSS over Akure, Nigeria. 2012. *Applied Physics Research*. vol. 4 (2): pp. 105–109.
27. C. Carter. *Principles of GPS Positioning: A Brief Primer on the Operation of the Global Positioning System.* CSR Technology, Inc. 2012.
28. D. Wyatt and M. Tooley. *Aircraft Communications and Navigation Systems*. Routledge. 2013.
29. G. S. Rao. *Global Navigation Satellite Systems*. Tata McGraw-Hill Education. 2010.
30. G. R. Dharani and N. B. Sabares. AEGPS (Accuracy Enhanced Global Positioning System) - Based on case study. *2012 International Conference on Information and Network Technology (ICINT 2012)*. 2012. vol. 37. pp. 183–187.
31. H. Peter Dana (Department of Geography. University of Colorado Boulder) (2004). *Global Positioning System Overview*. Retrived on September 26, 2014, from http://www.colorado.edu/geography/gcraft/notes/gps/gps_f.html.

32. T. J Jyrki. Penttinen. *The Telecommunications Handbook: Engineering Guidelines for Fixed, Mobile and Satellite Systems*. USA: John Wiley & Sons. 2015.
33. W. Xinlong and L. Yafeng. Study on adaptability of GPS ionospheric error correction models. 2009. *Aircraft Engineering and Aerospace Technology*. vol. 81(4): pp. 316 – 322.
34. M. S. Grewal, L. R. Weill, and A. P. Andrews. *Global Positioning Systems, Inertial Navigation, and Integration*. 2nd ed. New Jersey: John Wiley & Sons. 2007.
35. *Trimble-GPS Tutorial: How does Differential GPS works.* Retrived on January 23, 2013, from http://www.trimble.com/gps_tutorial/dgps-how.aspx.
36. T. Matsushita, T. Tanaka, and M. Yonekawa. Improvement of Measurement Accuracy with Long Baseline Reference Stations in DGPS. *Journal of the Institute of Positioning, Navigation and Timing of Japan*. 2011. vol. 1(1): pp. 1–8.
37. M. Chivers (2013). *Differential GPS Explained*. Retrived on February 21, 2015, from http://www.esri.com/news/arcuser/0103/differential1of2.html
38. K. Nagarajoo. Variable methods to estimate the ionospheric horizontal gradient. *8th IGRSM International Conference and Exhibition on Remote Sensing & GIS (IGRSM 2016).* 2016. IOP Publishing. vol. 37: pp. 012012.
39. K. Nagarajoo. Correction of the Ionospheric Horizontal Gradient for Better DGPS User Positioning. *International Journal of Engineering and Innovative Technology (IJEIT).* 2013. vol. 2(7): pp. 413–416.
40. J. Spencer, B. G. Frizzelle, P. H. Page, and J. B. Vogler. *Global Positioning System: A Field Guide for the Social Sciences*. John Wiley & Sons. 2008.
41. R. B. Langley. *Dilution of Precision*. GPS World. vol. 10(May): pp. 52–59. 1999.
42. R. Tiwari, S. Bhattacharya, P. K. Purohit, and A. K. Gwal. Effect of TEC Variation on GPS Precise Point at Low Latitude. *The Open Atmospheric Science Journal*. 2009. vol 3: pp. 1–12.
43. M. Richharia and L. D. Westbrook. *Satellite Systems for Personal Applications: Concepts and Technology Volume 22 of Wireless Communications and Mobile Computing*. John Wiley & Sons. 2011.

44. J. Frédéric Pont. *Alien Skies: Planetary Atmospheres from Earth to Exoplanets*. Springer. 2014.
45. Marshall Space Flight Center National Aeronautics and Space Administration (NASA) (2015). *Cycle 24 Sunspot Number Predictions*. Retrived on November 23, 2015, from http://solarscience.msfc.nasa.gov/images/Cycle22Cycle23Cycle24big.gif.
46. C. J. Schrijver, W. C. Livingston, T. N. Woods, and R. A. Mewaldt. The minimal solar activity in 2008-2009 and its implications for long-term climate modeling. *Geophysical Research Letters*. vol. 38(6): pp. 1–6, 2011.
47. The Old Farmer's Almanac (2013). *Solar Activity, Solar Cycle Predictions, and Sunspots*. Retrived on July 23, 2012, from http://www.almanac.com/sunspotupdate.
48. NASA Marshall Space Flight Center Solar Physic Group (2014). *Sunspot Cycle.* Retrived on September 15, 2014, from http://solarscience.msfc.nasa.gov/SunspotCycle.shtml.
49. O. F. Nneka, O. S. Ebere, and H. E. Akpan. Investigation of electron density variation in some regions of the Ionosphere at Nsukka, Nigeria. 2009. *International Journal of Library and Information Science*. vol. 1(2): pp. 12–16.
50. NOAA National Geophysical Data Center (2014). *Geomagnetic kp and ap Indices.* Retrived on October 19, 2014, from http://www.ngdc.noaa.gov/stp/geomag/kp_ap.html.
51. NOAA National Geophysical Data Center (2014). *Selected Geomagnetic And Solar Activity Indices.* Retrived on October 19, 2014, from ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/KP_AP/kp_ap.fmt.
52. S. K. Leong, T. A. Musa, K. Omar, M. D. Subari, N. B. Pathy, and M. F. Asillam. Assessment of ionosphere models at Banting: Performance of IRI-2007, IRI-2012 and NeQuick 2 models during the ascending phase of Solar Cycle 24. *Advances in Space Research.* 2015. vol. 55(8), pp. 1928–1940.
53. International Reference Ionosphere - IRI-2012. (2016). Retrived on March 19, 2016, from http://omniweb.gsfc.nasa.gov/vitmo/iri2012_vitmo.html.
54. *TableCurve3D: Automated Surface Fitting Analysis* (2016). Retrived on March 19, 2016, from

http://www.sigmaplot.com/products/tablecurve3d/tablecurve3d_4_brochure.pdf

55. Trimble Business Center. Version 2.70. *Release Notes*. Ohio. 2012.
56. Y. B. Yao, P. Chen, S. Zhang and J. J. Chen. Temporal and spatial variations in ionospheric electron density profiles over South Africa during strong magnetic storms. *Natural Hazards and Earth System Science.* 2013. vol. 13(2): pp. 375–384.
57. X. Zhang, X. Shen, J. Liu, Z. Zeren, L. Yao, X. Ouyang, S. Zhao, G. Yuan, and J. Qian. The solar cycle variation of plasma parameters in equatorial and mid latitudinal areas during 2005-2010. *Advances in Space Research*. 2014. vol. 54(3): pp. 306–319.
58. F. Ouattara, D. A. Gnabahou, and C. A. Mazaudier. Seasonal, Diurnal and Solar-Cycle Variations of Electron Density at Two West Africa Equatorial Ionization Anomaly Stations. *International Journal of Geophysics*. 2012. vol. 2012: pp. 9.
59. E. Mohíno Harris, M. Gende, and C. Brunini. A Method for Ionospheric Bias Mitigation in Differential GPS Positioning Using Multiple Reference Stations. *Journal of Surveying Engineering*. 2010. vol. 133(1): pp. 1–5.
60. C. Okorocha and O. Olajugba. Comparative Analysis of Short, Medium and Long Baseline Processing in the Precision of GNSS Positioning. *FIG Congress 2014 Engaging the Challenges - Enhancing the Relevance*. June 2014. pp. 7005.
61. S. K. Panda, S. S. Gedam and G. Rajaram. Ionospheric Characteristics of Low Latitude Anomaly Zone Over Indian Region by Ground Based GPS, Radio Occultation and SPIM Model Predictions. *IGARSS 2013*. pp. 1839–1842.