Delay Estimation of an Electromagnetic Wave Propagating Through Ionosphere Using Total Electron Content in GPS

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Abstract

The most famous and known effects of space weather is fluctuation in the amplitude and phase of the radio signal that propagates in the ionosphere. This fluctuation is also known as scintillation which will intense, degrades the signal quality, reduce the information content, or cause failure of the signal reception. The analysis of fluctuation can be used to predict the behavior of ionosphere during day time. Scintillation at the ionosphere during the day time seems to be different compared to night time. So, this research mainly focuses on the effect of ionosphere corresponding to delays. The method that will be used is analyzing the GPS Ionospheric delays and TEC Monitor data obtained from International reference Ionosphere. The result will be recorded in graph and tables to see the difference of parameter values during day time and night time for a day. The finding from this research is Total Electron Content (TEC) was increasing when sun radiation increases as well as range delay increases.

Keywords

GPS; Total Electron Content; Range and Time Delay; Appleton-Hartree Formula

I. Introduction

Ionosphere which is one of the Earth's atmosphere layers is a changing environment in both temporally and spatially. It is the basic guard of the Earth and life on Earth from the dangerous impact of the Sun and the cosmos itself and it extends to a height of about 50 to 1000km. Studies of shapes, temporal and spatial changes, characteristic regions and the frequent disturbances of the ionosphere have been prevalent in the past two decades due to the effects of the Sun, especially with the development of the GPS (Global Positioning System). Ionospheric research also attracts the GPS community as the phenomenon of ionospheric signal delay is one of the important sources of error for GPS measurements. On the other hand the application of GPS technology allows scientists to gain insight into the shape and behavior of the ionosphere. The signals sent from satellites must pass through the ionosphere on their way to Earth. Free electrons which are the most massive particles in the ionosphere affect the propagation of the signal like, changing their speed, direction and shape of the signal path. Positioning error that occurs due to this effect is called the ionospheric delay [5].

TEC, total electron content is the parameter that most affects the propagation of GPS signal. The results of this work are the numerical values of TEC and their cartographic representations, as well as spatial and temporal variations of TEC on the hourly level. Using data on these maps, the movement of electrons can be predicted and the necessary corrections in the GPS measurements can be calculated.

As per theory and Modeling Techniques, Ionosphere, one of the layers of the atmosphere, contains ions and electrically charged particles. The upper limit of the ionosphere is not clearly defined because at the altitudes over 1000km of the electron density gradually decreases, so it is difficult to determine precisely the transition from the ionosphere to the plasma sphere.

Ionosphere is divided into four smaller layers D, E, F1 and F2, each layer with special characteristics. Electromagnetic (EM) radiation from the Sun is the main source of energy that forms the ionosphere and it is in the form of solar Extreme - x radiation and Ultra Violet (EUV) radiation. Collisions of particles of EUV beam, called photons, with the atoms and molecules of gas in the atmosphere, can create enough energy for the occurrence of photonisation, forming positively charged ions (cations) and negatively charged free electrons. Recombination is the opposite process in the ionosphere, where the recombination of cations and free electrons take place to form neutral atoms and molecules.

Merging of free electrons with neutral atoms and molecules by which negatively charged ions (anions) are created is another phenomenon. However, anions and cations which have very little effect on the propagation of EM waves because of the relatively large mass and inability to oscillate when they are exposed to EM wave. Therefore, this paper mainly made reference to the effect of free electrons on the propagation of EM waves [2].

II. Propagation of Electromagnetic Waves affected by Ionosphere.

There are two effects when radio waves emitted from GPS satellites pass through the ionized path: the trajectory of the beam is bent and the signal comes to a destination with a delay. The free electrons in the ionosphere are the culprits [15]. To appropriately describe the behavior of radio waves passing through the ionosphere, it must be borne in mind that the ionosphere is only partially ionized, which extends along the uneven magnetic field, which is distorted in itself because of the disorder that arises as a result of the occurrence of solar winds.

In ionosphere, the refractive index is a complex quantity, which Edward Appleton has described in his magnetic-ionospheric theory. He demonstrated first that when going through the magnetized plasma, a plane polarized wave splits into two circularly polarized waves rotating in opposite directions. Hartree suggested that the Lorentz polarization should be applied in the theorem, so the formula for calculating the complex refractive index was named Appleton-Hartree formula [2].

Appleton-Hartree formula refers to an environment that is electrically neutral, and does not result in any charge in space and with an equal number of electrons and cations, which extends along a constant magnetic field, and the effect of cations on the wave is negligible.

Let a plane EM wave travel along the x axis of orthogonal coordinate system and a uniform external magnetic field lie in x-y plane forming an angle T with the direction of wave propagation. The complex index of refraction given by Appleton-Hartree formula reads:

$$n^2 = 1 - \frac{X}{(1-iZ)-\left[\frac{Y_T^2}{2(1-X-iZ)}\right]\pm\left[\frac{Y_T^4}{4(1-X-iZ)^2}+Y_L^2\right]^{\frac{1}{2}}} \qquad (1)$$

or generally:
$n^2 = 1\text{-}F(f, f_N, f_H, f_c, \Theta)$
where n is the complex refractive index (μ-iχ), with real part μand imaginary part χ.
Further applies:

$$X = \frac{W_N^2}{W^2} = \frac{f_N^2}{f^2}$$

$$Y = \frac{W_H}{W} = \frac{f_H}{f}$$

$$Y_L = \frac{W_L}{W} = \frac{f_L}{f}$$

$$Y_T = \frac{W_T}{W} = \frac{f_T}{f}$$

$$Z = \frac{W_c}{W} = \frac{f_c}{f}$$

where f[Hz] - carrier frequency; ω [radian/s] – angular frequency of the carrier wave;
f_N [Hz] – frequency of the plasma; [radian/s] – angular frequency of the plasma, which is calculated according to the formula $W_N^2 = \frac{Ne^2}{\epsilon_o m}$ with density of electron N [electrons/m^3, charge e (1.6 x10^{-19}C), dielectric permittivity of free space ϵ_0 (8.8542 x10^{-12} F/m) and the electron mass m(9.1095x10^{-31} kg);
f_H [Hz] – gyro frequency of free electrons; ω_H [radian/s] – angular gyro frequency, which is calculated according to the formula $W_H = \frac{B_o|e|}{m}$, with magnetic induction B_0[T = Wb/m^2];
f_L [Hz] – longitudinal gyro frequency; ω_L [radian/s] – longitudinal angular gyro frequency, which is calculated according to the formula $W_L = \frac{B_o|e|}{m}\cos\theta$;
f_T [Hz] – transverse gyro frequency; ω_T[radian/s] – transverse angular gyro frequency, which is calculated according to the formula $W_T = \frac{B_o|e|}{m}\sin\theta$;
f_C [Hz] –frequency of collisions between electrons and heavy particles; ω_C – angular frequency of collisions;
θ – angle between the signal and the vector magnetic field.
Equation (1) can be developed in endless series. If collisions (Z≈0) and the influence of magnetic fields (θ ≈0) are neglected, then we can take only the first two terms:

$$n = 1 - \frac{1}{2}\left(\frac{f_N^2}{f^2}\right)$$

Given, that for each point f_N^2 =80.6 N Hz^2 is valid (N is the density of electrons in electron/m^3), pure carrier wave can be calculated as follows:

$$n = 1 - 40.3\frac{N}{f^2}$$

For the ionosphere it can be written:

$$n_p = 1 - 40.3\frac{N}{f^2} \tag{2}$$

where n_p is phase refractive index, which is equivalent to equation (8), while the group refractive index is:

$$n_g = 1 + 40.3\frac{N}{f^2} \tag{3}$$

In reality, it is not geometric, but electromagnetic distance that is generally measured between the satellite and the receiver. This distance can be written as:

$$S = \int_{satellite}^{Reciever} n\,ds \tag{4}$$

Substituting equation (2) in (4) we obtain:

$$S = \rho - 40.3\,\frac{1}{f^2}\int_{Satellite}^{Reciever} N\,ds$$
$$= \rho - 40.3\,\frac{TEC}{f^2} \tag{5}$$

where TEC is total electron content, i.e. integrated electron density along the signal path given in the TEC units (1 TEC = $10^{16}\frac{1}{m^2}$) and ρ is the right distance. The equivalent expression for the modulated signal reads:

$$S = \rho + 40.3\,\frac{TEC}{f^2} \tag{6}$$

From equation (5) and (6), it follows that during the passage through the ionosphere, phase of the carrier wave will accelerate (the distance S is shorter than the actual distance ρ) and the modulated signal will be delayed (the distance S is longer than the actual distance ρ). Given that the value of ρ is the true distance from the satellite to the receiver, the second part of above equations represents the error caused by signal propagation through the ionosphere, known as ionospheric signal delay, i.e.:

$$R_{d\ iono} = 40.3\,\frac{TEC}{f^2}$$

$$T_{d\ Iono} = \frac{R_{d\ iono}}{c}$$

Table 1: Ionospheric Parameters for a Complete Day of 18th June 2016

TIME IN HOURS	TEC in TECU	RANG DELAY in METERS	TIME DELAY in nano SECONDS
1	6.8	1.10	3.68
2	5.9	0.96	3.2
3	4.5	0.73	2.44
4	3.6	0.58	1.95
5	4.6	0.75	2.49
6	8.7	1.41	4.71
7	14.6	2.37	7.91
8	19.3	3.14	10.5
9	22.1	3.59	12
10	25	4.06	13.5
11	29.2	4.74	15.8
12	33.6	5.46	18.2
13	36.6	5.95	19.8
14	38.4	6.24	20.8
15	38.9	6.32	21.1
16	37.9	6.16	20.5
17	34.7	5.64	18.8
18	28.9	4.70	15.7
19	21.3	3.46	11.5
20	14.2	2.31	7.69
21	9.6	1.56	5.2
22	7.6	1.23	4.12
23	7	1.14	3.79
24	7	1.14	3.79

Since the frequencies of GPS signal are known (i.e.L1 band=1575 MHz), it follows that ionosphere signal delay is the only function of TEC. Hence it can be concluded that the knowledge of TEC and its characteristics allows the modeling of the ionosphere for scientific purposes (e.g. forecasting of solar storms on the basis of developments and changes in the number of electrons), the determination of error propagation of radio waves, etc [4].

III. TEC Mapping Results

Mapping the obtained TEC values from Table 1 is performed using MATLAB. Below are some examples of time TEC maps for a complete day. Using these maps the movement of electrons can be monitored and the value of the TEC can be read. By tracking the movement we can predict the expected geomagnetic period. With a good forecast of geomagnetic period and design of measurement performance time plan, it is possible to reduce the impact of ionospheric refraction. It is shown in fig. 2 that ion density or electron density increases with respect to day temperature represented in fig. 1.

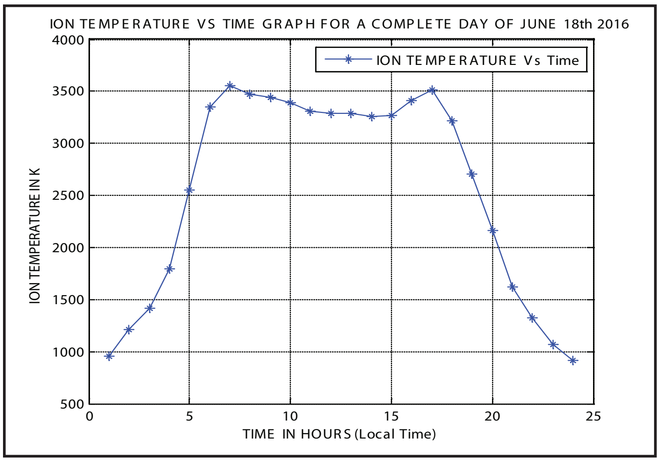

Fig. 1: Ion Temperature for a Complete Day of 18th June 2016

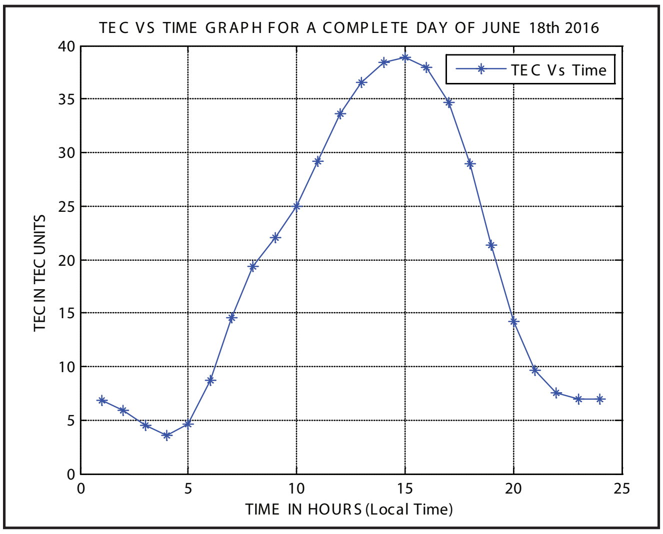

Fig. 2: TEC for a Complete Day of 18th June 2016

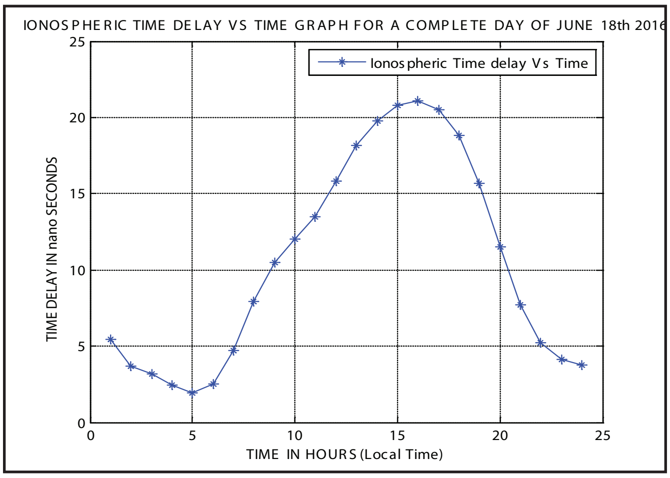

Fig. 3: Ionospheric Time Delay for a Complete Day of 18th June 2016

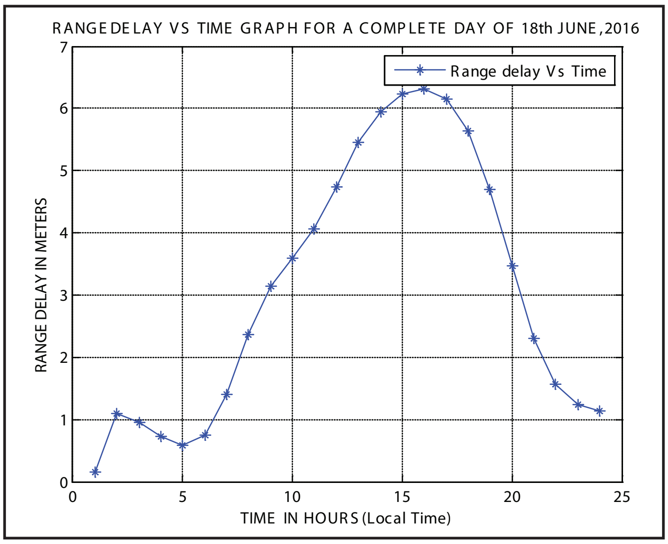

Fig. 4: Ionospheric Range Delay for a Complete Day of 18th June 2016

Due to increase in electron density in ionospheric layer, according to equation (5) and (6) range delay and time delay vary. These variations are plotted in fig. 3 and 4.

IV. Conclusion

GPS has a great significance in scientific research. Satellites orbiting the Earth at an altitude of 20.200 km, send signals that, on their way to the receiver, pass through the ionosphere which extends from 50 - 2000 km above the Earth's surface. The free electrons that are found in this region of the atmosphere, affect the propagation of the signal, changing the speed and direction of propagation of the signal. Due to inhomogeneity of the ionosphere, the direction of propagation of the GPS signal is curved.

The influence of the ionosphere can cause positioning errors for users who need highly accurate measurements. The ionospheric parameter that has the greatest impact on radio signals beamed from satellites is the Total Electron Content (TEC). Propagation delay is proportional to the TEC along the signal path from the satellite to the receiver. TEC is defined as the integral of the electron density per square meter along the path through which the signal is transmitted.

This paper presents a model for collecting and processing the TEC. We used observations of data from IRI Model, which were later processed with the appropriate software. Variations of the total electron content during the day were displayed. The peak value of the TEC was between 2pm and 4 am, after which the value was declining. Based on the analysis it can be concluded that for the purposes of accurate measurements, the application of these methods is acceptable only if the phase and code measurements are combined. However, the aim of this study was not to achieve accuracy, but to show the possibilities that Global Positioning System offers.

References

[1] Klobhuchar, J.A.,"Ionospheric time-delay algorithm for single-frequency GPS users", IEEE Trans AerospElectron Syst.,23(3), pp. 325-331, 1987.

[2] G.S.Rao,"Global Navigation Satellite System", Tata McGraw Hill Publication, 2010.

[3] "Determination of TEC in the ionosphere using GPS Technology", UDC:627.7, DOI:10.14438/gn.2014.22, Review article.

[4] Shaik Gowsuddin, Dr V B S Srilatha Indira Dutt 2012- Ionospheric Parameters Estimation for Accurate GPS Navigation Solution, pp. 302 – 305(IJEAT).

[5] SpilkerJJ, Parkinson BW (eds) Global positioning system: Theory and applications, Vol. 1. AIAA, pp. 485–515.

[6] V.B.S.Srilatha Indira Dutt et al,“Investigation of GDOP for precise user position computation with all in view and optimum four satellite Configurations”, Journal of Indian Geophysical Union, Vol. 13, Issue 3, pp. 139-148, 2009.

[7] [Crawford, 1968] Crawford, F., 1968. Berkeley Physics Course, Vol. 3 WAVES. McGrawHill, Inc., New York, USA.

[8] Gleason S., Gebre-EgziabherD.: GNSS Applications and Methods, ArtechHouse. Boston/London, 2009.

[9] Klobuchar, J. A.,“IonosphericEffectsonGPS,” Global Positioning System: Theory and Applications, edited by B.W.ParkinsonandJ.J.

[10] Aarons.J.Klobuchar, J.A.Whitney, H.E.Austen, J.Johnson. A.L., Rino, C.L.,“Gigahertz scintillations associated with equatorial patches”, RadioScience, Vol. 18, No. 3, pp. 421–434, 1983.

[11] Komjathy, A.,"Global Ionospheric Total Electron Content Mapping Using the Global Positioning System", 1997.

[12] RTCA,Inc.,“Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment”, RTCADO-229D, December 13, 2006.

[13] Kaplan.E.D., Hegarty.C.J.,"Understanding GPS Principles and Applications, 2ed. Norwood: Artech HouseInc., 2006.

[14] Surendran Shanmugam, Jason Jones, Allan MacAulay, 2012- Evolution to Modernized GNSS Ionospheric Scintillation and TEC Monitoring, IEEE/ION PLANS 2012-april24-26,Myrtle Bwach, SC, Session B2A

[15] Mahesh Babu Katta, R.Priyakanth, Tejaswini Kunam, “A Systematic Study of Estimation of Ionospheric Delay Errors in GPS”, International Journal of Scientific Research Publications (IJSRP), Vol. 7, Issue 1, pp. 97-101, 2017.

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