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Ionospheric Affects on GPS Signals.

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Abstract*- The paper is all about the study of Ionospheric effects on the GPS signals. For the better understanding the construction of Ionosphere is also defined. In this paper, some of the approaches are discussed that can reduce the error in the GPS signal. The main purpose of this paper is to provide knowledge of the ionosphere as it relates to space transmission techniques. Especially, the most informative technologies like GNSS (global navigation satellite systems), and the fully deployed and operational global positioning system (GPS). In the paper other features that would be more focused are travelling Ionospheric disturbances, solar flares, Ionospheric storms and scintillation. Scintillation is a rapid amplitude and phase fluctuation of satellite signal observed near the earth's surface. It is a main problem in Navigation application using GPS and in satellite communication. Especially in low latitude, the problem is more prominent around irregular equatorial peak region. Severe amplitude fading and strong scintillation affects the reliability of GPS navigational system and satellite communications.

Keywords- *Ionospheric effects, Ionospheric modeling, Coronal Mass Ejection, Scintillation, Pseudorange Error, GNSS and GPS. Travelling Ionospheric Disturbances*

I. INTRODUCTION

Before Global Navigation Satellite Systems were introduced to the market, Ionospheric sounding was much limited than nowadays in terms of spatial and temporal sampling. The amount is ionosondes are very partial and provide direct relation of the electron density profile in the bottom layer present. These relations are obtained through a number of measurements of the travel times of two-way electromagnetic (EM) signals for an increasing series of frequencies.

However, in the GNSS, the dual-frequency global positioning system (GPS) has become a type of global scanner of the Earth's ionosphere, or an *ionoscope*. To provide an overview of ionospheric science as it relates to space geodetic techniques.

Let us elaborate this paper in terms of sections so that it becomes easy to understand. For this let us follow elaboration as

a. Morphology of Ionosphere,
b. GNSS model in ionospheric sounding,
c. Electron content monitoring from GNSS data,
d. short-term ionospheric variability
e. How ionospheric knowledge merits in space geodesy.

II. IONOSPHERIC MORPHOLOGY & CONSTRUCTION

Firstly to understand that what type of effects ionosphere puts on our GPS signals we need to understand what ionospheres is and what are the different variations that it undergoes that can affect our signal.

Ionosphere typically extends from approximately 70 to 1,000 km above sea level and has its maximum effects found at heights of a few hundred kilometres that is the altitude coinciding with the highest ionization (i.e., where the combination of abundant extreme ultraviolet (EUV) and X-ray solar radiation intensity and sufficient neutral atmospheric density cause an ionization maximum. The presence of ions and free electrons decreases above 1,000 km. This region contains ionized molecules, free electrons that significantly affect electromagnetic waves propagation. The main physical quantity adopted to characterize the ionosphere is the spatial and temporal distribution of the number of free electrons per volume unit (electron density N_e). Because of its prevalent effect on radio wave propagation associated with its charge mass ratio that is much higher than those of ions.

Most of the region is in a combined state and remain electrically neutral. In the ionosphere, however, solar radiation (generally UV light) is more intense that when it collides with gas molecules they get ionized and an electron is let free. Hence, the region consists of positive ion and a free electron. These leftover free electrons actually affect radio waves. The number of electrons starts to increase at an altitude of about 30 km, but the electron density isn't sufficient to affect radio waves until about 60 km. This is convenient for many explanations that ionosphere has distinct layers, but it's not utterly accurate as the entire ionosphere contains ionized molecules and redundant Instead, the layers are best thought of as peaks in ionization levels.

Basically, we can generalize ionosphere into 3 basic layers. Generally, they are represented by letters D, E and F. Not to overlook that there is a C layer, but its level of ionization is so low that it has no effect on radio waves. Electron levels fall quickly and the D layer effectively disappears. Above the D layer, the next ionization level is called the E layer. It can be found at altitudes between 100 and 125 km. As electrons and ions recombine relatively faster in this layer, ionization levels drop rapidly after daytime. Although a small amount of residual ionization persists, the E layer practically disappears at night. The most important layer for long-distance communication is the F layer. During the day it often splits into sub-layers we call F1 and F2. However, at night the two layers amalgamate back into a single F layer. Depending on the time of day, the term and the position of the sun F-layer altitudes differ considerably hence consider them as approximates. In bright day, the F1 layer may be at 300 km, along with F2 layer at $4x10^2$ km or more. In the

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winter, these figures may change to $3x10^{2}$ km and 200 km, respectively. After merging at night, the F layer is usually around $2.5x10^{2}$ to $3x10^{2}$ km. As with the D and E layers, ionization levels in the F layer decrease at night. The rate of recombination is much slower F layer comparatively to other layers, due to higher altitude and low air density.

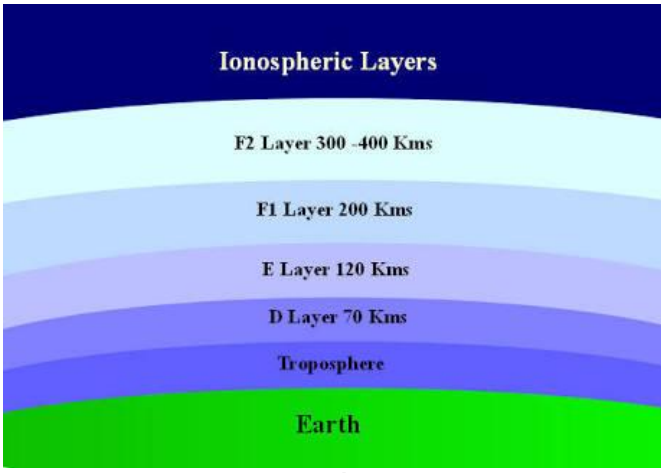

Figure 1 Ionospheric Layers

Due to the left over ionization which remains overnight can still affect radio signals. In the daytime, medium-wave signals propagate only via ground wave as the D layer absorbs signals which reach the ionosphere. As frequency is increased, signals pass through the D layer on to the E layer due to the drop in attenuation point. Here signals are reflected and pass back through the D layer and return to Earth to a considerable distance from the transmitter. E-layer refraction becomes less efficient as frequency increased further and the signals pass through to the F1 layer, where they may be reflected back through the D and E layers to reach Earth. Due to higher altitude of F1 layer than the E layer, the distance travelled by signals refracted by the F layer is greater. As frequency increases still further, signals will eventually pass through the F1 layer to the F2 layer. Because this is the highest reflecting layer, the distance spanned by signals reflecting from it is the greatest. When comparing the maximum skip distance covered by the signal, the skip distance for the E layer is about $2x10^{3}$ km. However, for the F2 layer that increases to about $4x10^{3}$ km which is significantly large then the prior.

III. CAUSES OF ERRORS

The GPS signal is very sensitive to the distribution of free electrons in the ionosphere, these free electrons which responds to the EM field, oscillating and generating a secondary EM wave that interferes and changes the velocity of the GPS signals. In other words we can say that these electrons affect our GPS signal the most and changes amplitude and phase. Hence, GPS is an excellent ionospheric sounding system which can help us in revealing new and detailed knowledge of electron content distribution, particularly in terms of electron content variability, due to ionospheric storms, solar flares and scintillation. Some of these views are briefly summarized in the following.

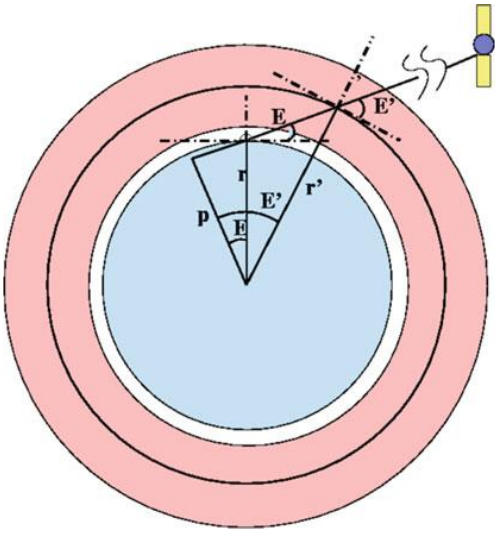

Figure 2 Signal receptions from satellite.

Ionospheric Storms: Ionospheric storms are amongst the main disturbances occurring in the ionosphere, and these events are typically associated with the arrival of a powerful solar wind, typically with Coronal Mass Ejection (CME) events occurrence during solar flares, which in return can produce elevated temporal and spatial inconsistency of the electron density distribution. This inconsistency occurs principally when southward ecliptic component is present in the interplanetary magnetic field component which is close to the Earth. In this manner, it reconnects with the geomagnetic field, inducing particle precipitation at high latitudes over the auroral regions, producing significant changes in electric fields. Records of EGNOS and Satellite based Augmentation Systems have data justifying the effect of ionospheric storms producing integrity problems in ionospheric modelling. Enhancements up to level of tens of TECU's have been notices.

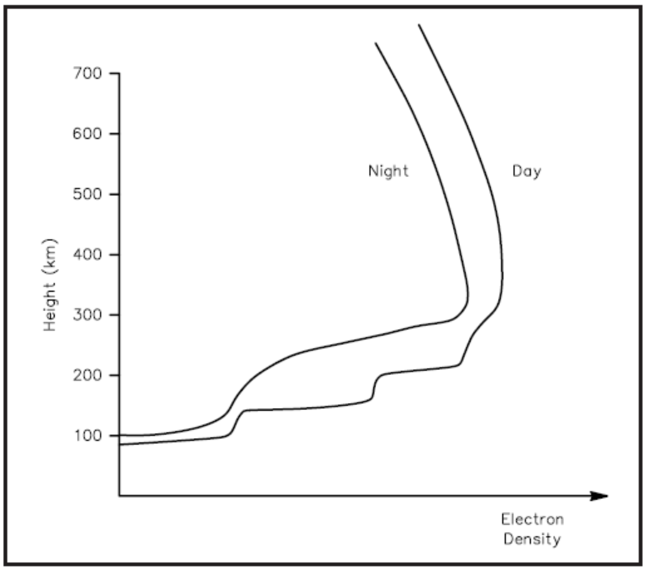

Figure 3 Electron density irregularities in ionosphere

Travelling Ionospheric Disturbances (TID): We can define are plasma density disturbances that propagate as waves through the ionosphere in a large range of velocities and frequencies. TID's have been observed in most of the ionospheric measurements as Very Large Base Interferometry (VLBI), Incoherent Scatter Radar (ISR), GPS, and Faraday rotation measurements of polarized EM waves transmitted from satellites .Those waves which are proportional to electron content and geomagnetic field projection to the LOS. We can categorize TDI's in Large-Scale TIDs (LSTIDs) and Medium-Scale TIDs (MSTIDs). LSTIDs are present for a period longer than 1 hour and move faster than $3x10^2$ m/s. These are related to geomagnetic activity and Joule-effect heating at high latitudes, which produce thermospheric waves at lower latitudes. MSTIDs have shorter periods ranging from 10 min to within 1 hour. MSTIDs are slower moving with speed from 50 to $3x10^2$ m/s. The origin of MSTIDs seems to be related to meteorological phenomena such as neutral winds or the solar terminator that produce atmospheric gravity waves manifesting as TIDs at ionospheric heights. This type of TID, which more frequently affects space geodesy users, in terms of the season and local time, will be discussed in more detail in the following section.

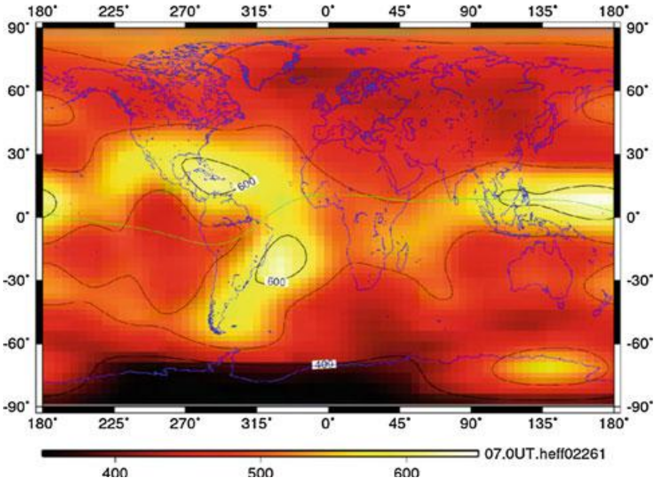

Figure 4 GPS ionospheric effective height (in km) computed by the Technical University of Catalonia (UPC) from global IGS.

Medium scale TIDs: MSTIDs are wave-like signatures appearing in the STEC, with typical amplitudes of several TECU and wavelengths ranging from 100 to 300 km. These TDI's show strong seasonal behaviour at mid latitudes related to the solar terminator and associated atmospheric gravity waves, in a way that they mostly occur on winter. Pattern of movement moving toward the equator with a typical horizontal velocity of $1x10^2$–$2.5x10^2$ m/s in summer moving westward with velocities of 50–$1.5x10^2$ m/s. This type of behaviour for seasonal changes makes MSTIDs modelling reliable application implementation e.g. GNSS. MSTIDs have small amplitude of tenths of a TECU. A small variation can cause (ionospheric disturbances) significant performance degradation in precise GPS navigation. Hence, the differential Ionospheric delays should be calculated with very high precision at least $2.5x10^{-1}$ TECU .Significant example is Wide Area Real-Time Kinematic, WARTK. High pass filter can easily detect MSTIDs over mid latitudes.

Solar flares: According to NASA, there are many kinds of eruptions on the Sun. This type of eruption involves massive explosions. Solar flares occur on the surface of the Sun and are generated near sunspots. These explosions involve emission of radiation throughout the entire electromagnetic spectrum and numerous ejections of charged particles. The spectrum produced by a solar flare in the UV and X-ray bands is particularly significant for the ionosphere. A significant part of the ejected particles combination of electrons, protons and heavier nuclei moving with non-relativistic velocities which can take up to 2 days or longer to reach the Earth surface. These masses follow the Interplanetary Magnetic Field (IMF) lines. Analysing the pattern of this mass can be of great help as it can serve the purpose to predict ionospheric storms. This is possible because the radiation reaching Earth keeps the originality and doesn't go under any particle enhancement. However, these radiations change the Total Electron Content of the ionosphere. This is why the TEC variation in the day and night in the ionosphere can be observed, for this GNSS receiver can be used. One simple and efficient way of detecting solar flares is by applying the day-to-day STEC variation technique to detrend the STEC and easily obtain the corresponding VTEC variation from the direct ionospheric carrier phase observations [1][4][6]. Double differences in time can allow better detection of the event characteristic times

Scintillation: The scintillation is caused by space weather changes such as solar flares which have a significant effect on the Earth's magnetosphere. Scintillation is an evening effect when the E-region combines decreasing its conductivity. The recombination and electric and magnetic drift in the F-layer gives rise to a steep electron density gradient. This causes difference in the concentration of densities of free electrons in the ionosphere and when disturbed can vary and scatter the radio signals. This is called scintillation. As we know for accurate functioning of the GPS we use four satellite model in which 3 satellites are used for the special position and one for time. Two types of scintillation can be found namely amplitude and phase scintillation. Amplitude scintillation can be found at lower latitudes is of random nature which can drop the signal level below the required signal threshold in GPS receivers required for maintaining lock or it can enhance the signal to a limit that can destroy the GPS receivers. On the other hand phase scintillation can be found at higher latitudes and cause rapid phase change in the carrier signal which makes it difficult to track the signal. Due to this GPS receivers can suffer phase lock loss and cycle slip.

GPS receiver can collect data of scintillation magnitudes and frequencies at different propagation paths. This collected data can be used to study ionosphere and develop appropriate operational models so that the GPS signal can overcome the effects of scintillation.

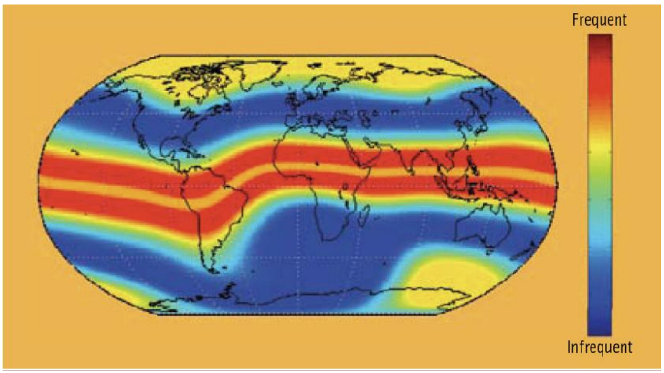

Figure 6 Scintillation effects

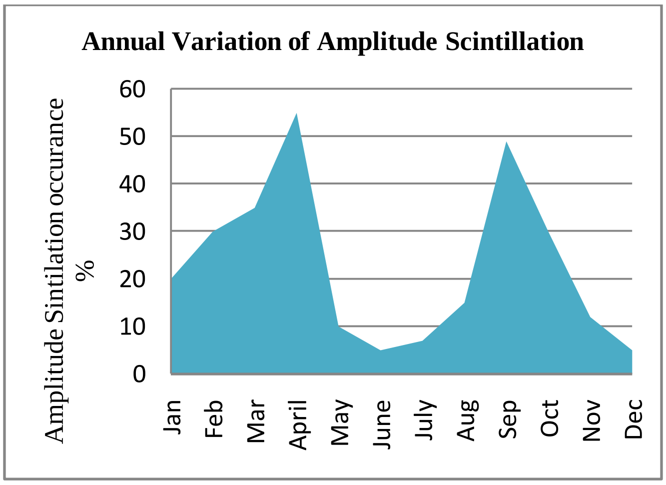

Figure 7 Monthly percentage of the occurrence of scintillation.

Figure 7, shows the mean amplitude scintillation occurrence in percentage per month recorded. From the figure it is clear that the scintillation in more in the months of April and September. However, the peak in the month of April is much higher than in September. It also shows that the occurrence of scintillation is more frequent in the Euqinox months (March, April, September, October) and least in summer months.

IV. IONOSPHERIC CORRECTIONS

There are lot of inconsistencies in our atmosphere which affect our GPS signal's strength and speed. It is very tedious tasks to overcome all of these at once. These errors are greater when the satellite is at far distance then the satellite which is overhead. We can compensate these errors by implementing appropriate mathematical model once the location of the receiver is approximated. A good knowledge of the ionospheric free electron content distribution of ionosphere can give us an advantage in correction of higher order ionospheric effects. However, this combination of carrier phase measurements only corrects the first order ionospheric term, the high order ionospheric terms can be greater than 1 cm in such combination. We must take into consideration the second and higher order ionospheric terms if the precision in millimetre level is needed in the devices of the positioning model. To eliminate the higher order ionospheric terms from the approximate of code or carrier measurements, we need to consider Slant Total Electron Content from the data collected by the GPS receiver. We can user a preinstalled ephemeris code in the satellite or the device. This can eliminate the clocking error in the GPS signal running on a carrier.

Pseudorange Error: The group delay of the GPS signal introduces a range error into the pseudo ranges measured with the P-code or the *C/A-code*. The range error is obtained by multiplying the group delay by the speed of light (about 300,000) kilometers per second). The ensuing range error introduced by the earth's ionosphere can vary from less than 1 meter to more than $1x10^2$ meters and changes with time of day, season, and position of the receiver on the earth's surface, screening direction, solar activity, and the status of the earth's magnetic field. Over a single GPS satellite pass, if the ionosphere does not change significantly during the pass. The single-frequency user can take benefit of an ionospheric correction model, the coefficients of which are transmitted as part of the GPS satellite message. The correction algorithm was designed to reduce the group delay error by approximately fifty percent in a root-mean-square (rms) sense. Comparisons or the correction model against actual GPS dual-frequency tracking data have shown that this design goal has been exceeded by almost 10 percent [4].

The ionospheric correction algorithm models the diurnal ionospheric variation with a set of numerical coefficients. These coefficients are updated at 10-day intervals, or more often if necessary, to account for seas goal and solar activity changes. After applying this correction algorithm to single-frequency pseudo ranges. The remaining residual range error is due to short term ionospheric range errors not accounted for by the model. Because of new developments in code-free GPS receiver design the single-frequency user is not necessarily stuck with the 50 to 60 percent rms correction provided by the single-frequency ionospheric correction algorithms. Private industry and government research laboratories have developed code-free methods for the direct measurement of GPS range errors due to the ionosphere. Such instrumentation will more fully correct single-frequency measurements for ionospheric range errors.

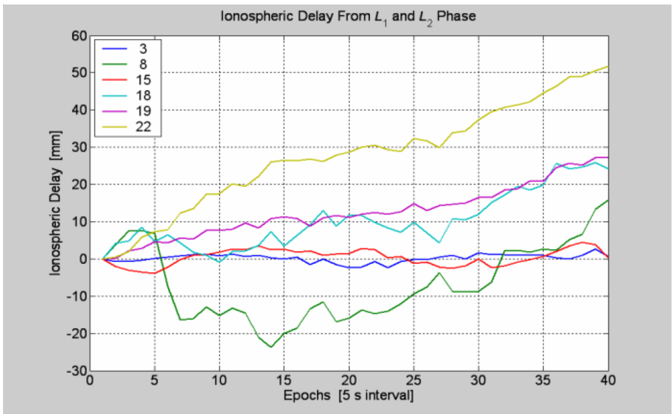

Figure 8 Depicted results of different satellites. T, the ionospheric delay ranges from 0.6 metres to -1.4 metres, 2015.

The ionosphere in the absence of selective availability can be

the greatest source of range and range rate errors for GPS users. The Dual frequency automatic correction for these effects is the best solution and the single frequency user can correct for approximately 50 to 60 percent of the rms range error using the coefficients transmitted as part of the satellite message. As an alternative, a separate relatively inexpensive, code free ionospheric monitoring receiver will soon be availability to measure ionospheric range error from all visible satellites simultaneously. All GPS users should be aware of the likely times and regions of strong amplitude fading and phase scintillation effects and should attempt to avoid positioning at those times and in those regions when possible.

Real-Time GNSS Meteorology: GNSS can be used to determine accurate and high frequency atmospheric parameters Zenith Total Delay (ZTD) in all weather conditions. The knowledge of the ionospheric STEC for the Line of Sight GPS system in multifrequency receivers can help us in strong reduction of convergence time in the computation of B_c. Zenith tropospheric delay can be computed more accurately[1]. Making these estimates in the real time from a warm start or after a few minutes from a cold start representing a significant improvement, compared with the time typically needed for B_c convergence in permanent receivers. Most of the real time geodic applications can be corrected by using new reduced B_c estimation and data of Zenith tropospheric delays. These then can be implemented in the Real Time GNSS or Weather Forecasting Models to increase their effectiveness.

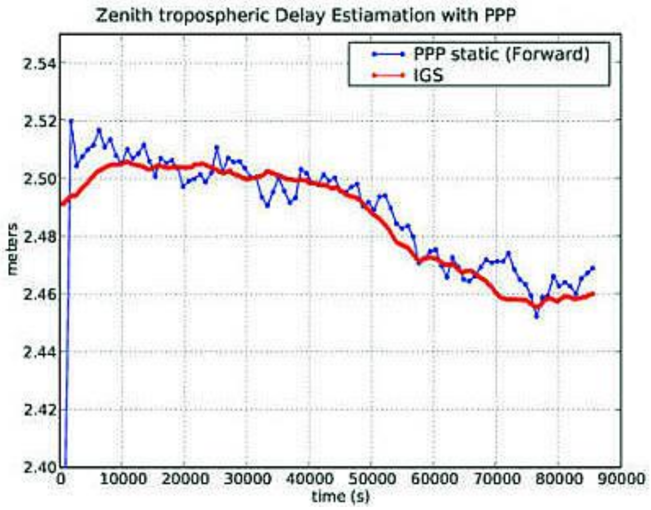

Figure 9 Ionospheric delay between (00:09 - 01:05), 2015.

V. CONCLUSION

In this paper an attempt has been made to show how GNSS can be improved with better understanding of ionospheric conditions. This paper summarizes some of the main ionospheric analysis and how this can help us in achieving better performance for GNSS systems, real-time weather forecasting models. This paper also provides significant ionospheric aspects and their effects on space geodetic techniques.

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