# INVESTIGATION OF THE GPS SIGNALS IONOSPHERIC CORRECTION

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## ABSTRACT

The purpose of this work is to investigate a proper model to correct the ionospheric effect using single frequency GPS measurements, which it will be used in the artificial satellite orbit determination taking in account that satellite will be above 1000 km of earth's surface. When the GPS signals are transmitted from GPS satellite to receiver, they propagate through the ionosphere causing errors on the measurements which are the highest one on signal propagation. To achieve the highest possible positioning accuracies form GPS, the ionospheric errors shall be neutralized using some kind of model and/or measurement, and they have to be considered within the adjustment process. Using dual frequency GPS receivers, the ionospheric errors can be almost totally accounted for taking advantage of the ionosphere's dispersive nature. However, this work deals with real-time determination of an artificial satellite orbit with single frequency GPS receiver. So, some model of single frequency ionospheric correction must be used. Such investigation will define to which extent the ionospheric error can affect the final accuracy of the real-time determination when using the GPS constellation.

***Keywords:*** GPS signals, ionosphere, single frequency

## INTRODUCTION

The GPS System allows users to measure range and range rate information simultaneously from four satellites to determine user's position and velocity. Each satellite transmits a data stream called Navigation Message on L1 and L2 at a rate of 50 bps. This data stream contains: the satellite clock correction term; the clock reference time; the differential group delay and IODC (Issue of Date, Clock) term; the Ephemeris parameters for the transmitting satellite; the single frequency ionospheric correction terms; the coefficients to convert GPS time to UTC; the Almanac of all satellites (Leick, 1994).

Moreover, the GPS satellite signals transmit other data types which are code and carrier phase pseudoranges. They are acquired from the transmitted signal at two L-band frequencies, $f_1$ = 1575.42 MHz and $f_2$ = 1227.60 MHz. Except for corruption by clock errors, atmosphere delays, and instrumental delays, pseudorange is an absolute measurement of radio-metric range between a GPS satellite and a receiver. Among the error sources, the largest one comes from the delay when a signal travels through the atmosphere. Carrier frequencies below 30 MHz are reflected by the ionosphere and only higher frequencies penetrate the ionosphere.

There are two differences between the carrier phase and code pseudoranges which are: the carrier phase pseudorange is biased by an unknown integer number of cycles and it has a data noise much lower than code pseudorange, which makes it more precise.

To allow users to automatically correct the effects of both the range and range rate errors induced by the ionosphere, the secondary frequency was incorporated into the system. The dual frequency GPS receivers take advantage of the dispersive nature of the ionosphere and can eliminate the ionospheric errors, at least mathematically. For single frequency users, it was incorporated into the system a numeric model of ionospheric range error called Klobuchar's model.

## IONOSPHERIC EFFECTS IN THE GPS MEASUREMENTS

The atmosphere is usually subdivided into regions. These regions are based on common physical properties and appearances such as temperatures, composition, state of mixing, and ionization. With respect to signal propagation, it can be divided in troposphere and ionosphere. This division is made according to the different conditions of propagation.

The ionosphere covers the region between approximately 50 km and 1000 km above the earth and is characterized by the presence of free electrons. In fact the upper boundary of the ionosphere is not well defined since it can be interpreted as the electron densities thinning into the plasmasphere and subsequently the inter planetary plasma (Komjathy, 1997).

The ionosphere is a dispersive medium for radio waves implying that the refractive index is a function of the radio wave's frequency, the electron density, and to a minor degree, the intensity of the earth's magnetic field. The refractive index is given by:

$$n = 1 \pm \frac{c_2}{f^2} \tag{1}$$

where the positive signal is for carrier phase pseudorange and negative one is for code pseudorange, $f$ is the frequency, $c_2 = -40.3\ N_e$, $N_e$ is the electron density which is always positive.

After integrating the phase and group refractive indices along the path of the GPS signal, the range obtained between the satellite and the receiver which is different from the true geometric range by the amount called ionospheric error. The error is negative for the carrier phase pseudoranges (phases is advance; that is, the measured range is shorter than the geometric range) and positive for the code pseudoranges (a group delay; that is, the measured range is longer than the geometric) (Komjathy, 1997).

The ionospheric delay is proportional to the number of electron content (integrated density along the signal path) and inversely proportional to frequency squared used:

$$\Delta_{ION} = \frac{40.3}{f^2} TEC \tag{2}$$

where *TEC* is Total Electron Content and is given by:

$$TEC = \int N_e ds \qquad (3)$$

and $s$ is the path from satellite to the receiver. The density of free electrons varies strongly with the time of the day and the latitude. Therefore, the change of pseudorange measurement caused by the ionospheric refraction may be restricted to the determination of the TEC. However, the TEC itself is a fairly complicated quantity because it depends on sunspot activities, seasonal, and diurnal variations the line of sight which includes elevation and azimuth of the satellite, and the position of the observation site. Taking all effects into account, a GPS pseudorange may be wrong from about 15 m to 50 m (Hofmann-Wellenhof, 1994).

## THE DUAL FREQUENCY IONOSPHERIC MODEL

The expressions for the code and carrier phase ionospheric corrections on L1 and L2 derived from the dual frequency observations are given by (Strang, 1997):

$$P_{IF} = \frac{f_1^2}{f_1^2 - f_2^2} P_1 - \frac{f_2^2}{f_1^2 - f_2^2} P_2 \qquad (4)$$

$$\Phi_{IF} = \frac{f_1^2}{f_1^2 - f_2^2} \Phi_1 - \frac{f_1 f_2}{f_1^2 - f_2^2} \Phi_2 \qquad (5)$$

where $P_{IF}$ and $F_{IF}$ are the free ionospheric effect, $P$ is the code, $j$ is the carrier phase, $f_1$ and $f_2$ are the frequency on L1 and L2, respectively.

The figures 1 and 2 show the ionospheric errors of carrier phase and code pseudoranges, respectively. These errors have been obtained without the ambiguity solution and data pre-processing. According to Strang (1997), these errors should be around 0.5 to 1 m to carrier phase and around 4 m to code.

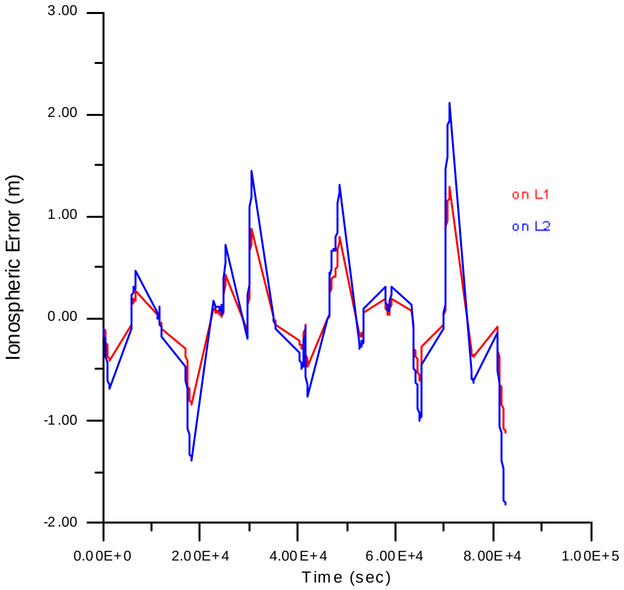

Figure 1: The carrier phase ionospheric error

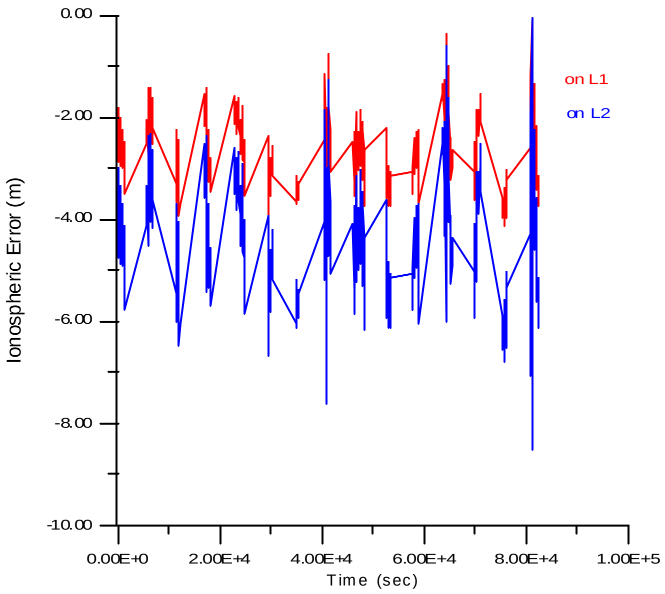

Figure 2: The code Ionospheric error

## KLOBUCHAR'S MODEL

The Klobuchar's model is used to correct the ionospheric effect for single frequency measurements. It uses the cosine model for the daily variation of the ionosphere, with the maximum being at 14:00 local time and is described by 8 coefficients α and β which are transmitted as part of the GPS satellite navigation message. This model removes about 50% of the total ionospheric delay at mid-latitudes and is represented through one set of variables that are valid for few days (Klobuchar, 1987). The ionospheric delay correction equation is given by (Seeber, 1993):

$$\Delta T_{ion} = DC + A\cos\left(\frac{2p\,(t-f)}{P}\right) \quad \text{(day)} \qquad (6)$$

$$\Delta T_{ion} = DC \qquad \text{(night)} \tag{7}$$

where $DT_{ion}$ is the vertical delay (ns), $DC$ is the constant midnight term (5 ns or $5\times10^{-9}$ sec), $A$ is the amplitude, $f$ is the constant phase term ($14^{h}$ local time), $t$ is the local time, $P$ is the period. The amplitude and period are functions of geomagnetic latitude and are represented by third-degree polynomials:

$$A = \sum_{n=0}^{4} a_n f_m^n \qquad \text{(seconds)} \tag{8}$$

$$P = \sum_{n=0}^{4} b_n f_m^n \qquad \text{(seconds)} \tag{9}$$

## EMPIRICAL MODEL OF THE EARTH'S PLASMASPHERE

This empirical model consists of an analytical expression that can be used to reproduce hydrogen density at arbitrary locations in the plamasphere for given conditions. The principal spatial dependence of plasmaspheric electron density is governed by L-shell. The L-shell is the surface traced out by a particle moving around the earth's geomagnetic filed lines. For the electron densities, the Gallagher model uses the following empirical formula (Gallaher *et al.*, 1988):

$$Log_{10}(N_e) = a_1 \bullet F(L) \bullet G(L) \bullet H(L) \tag{10}$$

where $N_e$ is de electron densities;

$$F(L) = a_2 - e^{a_3\left(1 - a_4 e^{-h(L,l\,)/a5}\right)} \tag{11}$$

is a modified Chapman layer;

$$G(L) = a_6 L + a_7 \tag{12}$$

is a linear L-shell model which has been found to be the best representation of the inner plasmaspheric electron density profiles;

$$H(L) = \left(1 + \left(\frac{L}{a_8}\right)^{2(a_9 - 1)}\right)^{-\left(\frac{a_9}{a_9 - 1}\right)} \tag{13}$$

represents the shape and the location of the plamaspause; and

$$\begin{aligned}
a_1 &= 1.4 \\
a_2 &= 1.53 \\
a_3 &= -0.036 \\
a_4 &= 30.76 \\
a_5 &= 159.9 \\
a_6 &= -0.87 + 0.12 e^{-x^2/3^2} \\
a_7 &= 6.27 \\
a_8 &= 0.7\cos\left(2p\,\frac{MLT - 21}{24}\right) + 4.4 \\
a_9 &= 15.3\cos\left(2p\,\frac{MLT}{24}\right) + 19.7.
\end{aligned} \tag{14}$$

The constants $a_i$ are free parameters used to fit equation to the logarithm of ion density. The parameter $a_6$ controls the density gradient in the inner plasmasphere, while $a_8$ and $a_9$ determine the location and slope of the plasmapause, respectively. L is the MacIlwain L-shell parameter, $\lambda$ is geomagnetic latitude, MLT is the geomagnetic local time defined by the geomagnetic longitude of the mean sun, and , h(L,$\lambda$) is the height above the earth's surface given by:

$$h(L, l) = R_e L \cos^2 l - 6371 \tag{15}$$

with a starting altitude of 1000 km above the surface of the earth; $R_e$ is the earth radius.

This model provides variations in the plasmaspheric electron density as a function of geomagnetic latitude, L-shell values, and geomagnetic local time. The algorithm does not model diurnal, seasonal or solar cycle variations of the plamaspehric electron content.

The ionospheric effect is calculated at each point. After this, it is necessary to calculate the effect along the path between the user and GPS satellites, that gives the TEC. Knowing the TEC, it is necessary to calculate the ionospheric effect that is given by:

$$\Delta I = \frac{40.3}{f^2} TEC \tag{16}$$

## CONCLUSIONS

The main goal of this study is to analyze and to choose a proper model to correct the ionospheric error on single frequency range measurements for an artificial satellite above 1000 Km. Despite being a model that providing good results, the dual frequency model can not be used in this work, but it will be used as reference model. The Klobuchar's model must be used for an user on earth's surface and it only corrects until 50% of the ionospheric error being necessary to use an estimation model to correct the unmodeled errors. The empirical model is a good model for an user above 1000 Km. However, through several analyzes, the ionospheric errors is very small above 1000 Km of earth's surface (around 1m) and it should be better to estimate them as parameters using Kalman filtering.

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