Comparison of ionospheric time delay due to BENT and IRI-90 electron density models for GPS in India

A D Sarma
R & T Unit for Navigational Electronics, Osmania University, Hyderabad 500 007

Received 15 April 1998; revised 17 September 1998; accepted 2 December 1998

The effect of ionospheric time delay on the performance of Global Positioning System has been described. The ionospheric time delay has detrimental effect on the ranging accuracy, next only to the error due to selective availability. Typical experimental results are presented. Time delay due to Bent and IRI-90 electron density models are compared. The necessity of a new ionospheric time delay model applicable to Indian conditions has been emphasized.

1 Introduction

The introduction of Global Positioning System (GPS) has led to a major improvement in the worldwide navigation facilities. With GPS, excellent navigation solutions can be obtained, the accuracy being limited by the precision in measuring the time delays and the extent of voluntary degradation, namely, selective availability (SA). The GPS provides user position (in 3-D), velocity and time in real time and that too continuously anywhere on or above the earth. The GPS consists of 21 satellites equally spaced in 6 orbital planes inclined at 55° to the equator along with 3 active spares. The satellites orbit the earth at about 20,180 km above its surface and have an orbital period of 12 h. The GPS satellite vehicles (SVs) transmit two navigational signals, namely, L1 (1575.42 MHz) and L2 (1227.6 MHz). Each satellite is assigned two pseudo-random noise codes, namely, P-code (precision code) and C/A-code (coarse/acquisition code) that are accessible to a particular satellite. The C/A-code is accessible to every one, whereas P-code, which can provide higher accuracies, is accessible only to authorized users.

A GPS radio signal which penetrates the ionosphere gets modified by the medium due to the presence of electrons and earth’s magnetic field. The effects include scintillation, absorption, variation in the direction of arrival, propagation delay, dispersion, frequency change and polarization rotation. The effect of some of these parameters on Communication, Navigation and Surveillance are discussed elsewhere. Out of all these effects the ionospheric time delay has the most detrimental effect on the ranging accuracy of GPS, next only to SA. Various time delay error models have been developed to model the ionosphere which would reduce the ionospheric time delay error to a considerable extent.

2 Prominent ionospheric electron density models

The ionospheric models represent the properties of the ionosphere as accurately as possible as functions of geophysical indices, with some statistical description of their variability. The important parameter responsible for ionospheric time delay is the total number of electrons encountered by the radio wave on its path from the satellite to the system user. The total electron content (TEC) is a function of long and short term changes in solar flux, magnetic activity, season, time of the day, user location and viewing direction. Here we consider the following two models.

(i) Bent’s model

In the Bent model, only a few TEC measurements were available in low latitude regions. The whole Asia is represented by the data from two stations in Hawaii and Hong Kong. Klobuchar used this electron density model for time delay modelling. This is implemented in GPS receivers. Details on Bent’s model can be found elsewhere. As the TEC behaviour in many parts of the world has a diurnal maximum near 1400 hrs LT, Klobuchar made the peak amplitude of cosine curve to coincide with 1400 hrs LT in his time delay modelling. But for Indian conditions, it is known that peak amplitude occurs at different times. For example, it is reported that the peak amplitude occurs at 1500 hrs LT for.
Kurukshetra. In view of the above drawbacks, it is proposed to develop a time delay algorithm based on IRI-90 electron density model suitable for GPS applications in the Indian subcontinent.

(ii) IRI Model

The International Reference Ionosphere (IRI) is a standard empirical ionospheric model established on behalf of International Union of Radio Science (URSI) and Committee On Space Research (COSPAR). Its main purpose is to produce a reliable reference global model of the most important ionospheric parameters such as electron density and ion composition. The IRI was published by URSI in 1978 as ‘IRI-1979’ and then with a somewhat improved computing programme in 1980 under the title ‘IRI-1979’ by the World Data Center at Boulder, Colorado, USA. Considering the data obtained at more than 100 stations, over a period of more than 20 years, a computer programme has been established by the CCIR (1983), which constitutes the best available representation of such data. The global variations of the key ionospheric parameters are reproduced through a numerical computer programme using appropriate Legendre and Fourier series. As the model is inadequate in some regions, some improvements have been incorporated in the model more recently, and a new version (IRI-90) has been implemented. The IRI-90 model is based on experimental observations of the ionospheric plasma. Some of the most significant modifications made in IRI-90 for the calculation of the electron density profiles include:

(i) A new set of coefficients for the F2-region peak electron densities and peak heights, introduced as a new option in addition to the coefficients of the CCIR numerical maps.

(ii) An analytical representation for the middle atmosphere using LAY functions and improvements in the calculation of thickness parameters for the bottomside ionosphere.

(iii) Improvements in the E-region peak electron density variations.

(iv) Extension of the calculation profiles to plasmaspheric altitudes.

The comparative analysis made between the IRI model-predicted and the measured electron density profiles has shown, in general, a quite reasonable agreement. The Klobuchar model was tested against actual TEC from 18 different stations for a total of 490 station-months of data and showed that 50% of r.m.s ionospheric correction has been met. But no station from Indian subcontinent was included in the test procedure. Therefore, in the present work IRI-90 is chosen to estimate the electron density.

3 Ionospheric time delay model

The errors contributed by the ionosphere for a single frequency user can be reduced, though not completely eliminated by way of appropriate models. The propagation effects of ionosphere are very complex. Ionospheric time delay models that yield good results at one place can prove to be useless at other places.

The Klobuchar’s time delay model that is currently being used by the single frequency GPS users to compute the ionospheric errors is based on the worldwide empirical TEC models. The model consists of a time delay algorithm that uses the positive portion of a cosine wave during daytime and a constant offset during nighttime to model the diurnal behaviour of vertical time delay as a function of time of the day. The amplitude and period of the cosine function as a function of geomagnetic latitude are represented by third-order polynomials. The model can be expressed as,

$$\Delta T_{\text{ion}} = A_1 + A_2 \cos \left( \frac{2\pi (t - A_3)}{A_4} \right) / A_5$$  \hspace{1cm} (1)

where,

- $A_1$: Nighttime value \((5 \times 10^{-6})\)s
- $A_2$: Phase \((1400\, \text{hrs LT})\)
- $A_3$: Amplitude = $\alpha_1 + \alpha_2 \phi_m + \alpha_3 \phi_m^2 + \alpha_4 \phi_m^3$
- $A_4$: Period = $\beta_1 + \beta_2 \phi_m + \beta_3 \phi_m^2 + \beta_4 \phi_m^3$
- $\phi_m$: Geomagnetic latitude of the ionospheric subpoint

The $\alpha$’s and $\beta$’s are eight polynomial coefficients uploaded by GPS master control station (MCS) to the SVs. The set of coefficients for upload to the satellite is selected on the basis of the seasonal effects and solar flux evaluated at the time of the upload. The SV, in turn, transmits these down to the user in the navigation message. These parameters were computed from an empirical model of worldwide ionospheric behaviour derived by Bent. The
algorithm described, however, is a compromise of several factors such as present state of knowledge of temporal, diurnal and geographic variations of TEC.

Klobuchar originally intended to provide a correction of approximately 50% of the ionospheric range error. Comparing the algorithm against actual ionospheric TEC data, it has been shown that an overall reduction in r.m.s error could be up to 60% in the northern hemisphere. The accuracy varies with the data interval over which the measurements are averaged (reflecting variation with the 11-yr solar-flux cycle as well as season of the year), location (reflecting variation with the geomagnetic latitude), local time of day, satellite elevation angle, etc., giving a minimum average of 50% r.m.s error reduction.

4 Experimental results

Using a dedicated GPS receiver at National Geophysical Research Institute (NGRI) Hyderabad, several important parameters were recorded. As we are interested in the ionospheric time delay, we have studied the characteristics of delay of discrete events on couple of days. The variation of ionospheric time delay on two typical days is shown in Fig. 1. The two sets of data from the same satellite vehicle (SV) correspond to UTC time of 0540-0550 hrs. When interpreting these data with respect to Klobuchar model, some interesting points have been noticed. In one case the delay is increasing and in the other case the delay is decreasing. It is noticed that even for the same set of α's and β's at the same time on two consecutive days it differs by about 4-5 ns. This discrepancy can be explained as follows:

The Klobuchar model result is based on statistical results. To compare with that model, data over a period of couple of months may be needed. Discrete events may not agree with that model.

Following is a calculation given here as an example.

The data were collected at Hyderabad station located at 17°25'N, 78°33'E. The satellite was at an elevation of 33° and azimuth of 322°.

The ionospheric coefficients were: α = 0.7451×10^{-8}, 0.1490×10^{-7}, -0.5966×10^{-7}, -0.1192×10^{-6} and β = 9.92160×10^{5}, 1.31072×10^{5}, -0.65536×10^{5}, -5.89824×10^{5}. The time was 0530 hrs UTC (GPS time is assumed to be 9 s ahead of UTC).

This gives the following results:

Earth-centered angle, θ = 4.3962°
Subionospheric latitude, φι = 20.8809°N
Subionospheric longitude, λι = 75.6532°E
Geomagnetic latitude, φm = 11.4192°N
Local time, t = 37966 s
Slant factor, SF = 1.6860
Ionospheric delay, T_{iono} = 18.166 ns

The result thus obtained agrees well with the ionospheric delay recorded by the GPS receiver at the station. These calculations are based on the example given in Ref. 2. However, it is noticed that several printing mistakes have crept in that publication. These mistakes have been brought to the notice of Klobuchar and were subsequently revised. The above example can serve as a standard reference. A cosine model fit to the data is shown in Fig. 2.

5 Comparison of time delay algorithm based on IRI-90 model and Bent model

The IRI-90 model gives only the electron density values. However, TEC is needed for the estimation of time delay. Therefore, to calculate the ionospheric time delay for the subionospheric latitude and longitude values given in the previous example, the electron density values from 60 km to 2000 km are obtained from the model.

The TEC for a transmission path is the integral of the electron density along the path, and thus has the dimensions of number of electrons per unit area. That is, the area under the altitude vs. electron density curve gives the TEC. Trapezoidal method is used for
The maximum time delay for both cases is widely different. At certain timing of the day the difference between these two plots can be as big as 40 ns.

(ii) A wide discrepancy exists between the IRI-90 model's time delay and Klobuchar's model time delay during nighttimes, i.e., before and after the cosine model also. The reason for this discrepancy is that the Klobuchar's cosine model considers a constant time delay at nighttimes, but according to IRI-90 model the ionospheric time delay ranges from 20 ns to 40 ns even at nighttimes. The Klobuchar's model clearly underestimates the delay. This again confirms that Klobuchar's model is not appropriate for low latitude regions like India.

6 Conclusions
A detailed study is needed to assess the performance of Klobuchar model at different locations in India. As this model is based on TEC models which are more relevant to the West, a new and suitable model has to be developed for Indian conditions to improve the ranging accuracy of GPS in India. A time delay model based on IRI-90 electron density model is found to be a promising one and is expected to give more accurate results for the Indian subcontinent.

Acknowledgement
Thanks are due to National Geophysical Research Institute, Hyderabad, for providing the experimental data to the author.

References