J. Ind. Geophys. Union (October 2004)
Vol.8, No.4, pp.319-327

Ionospheric Time Delay Estimation using IDW Grid Model for GAGAN

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ABSTRACT
To facilitate the accuracy required for Category-1 (CAT-1) precision approach landing of aircrafts, augmentation of GPS is planned through regional SBAS called 'GAGAN' by Indian Space Research Organization (ISRO) and Airport Authority of India (AAI). In GAGAN, ionospheric time delay is one of the predominant errors that limit the range accuracy of the user. Even though several analytic function based models are available for ionospheric error corrections, grid based models are preferred due to their greater accuracy and less complexity. The accuracy of modeled vertical ionospheric delays at the IGPs, user's IPPs and GIVE are the functions of IPP density, grid size, input data and measurement update rates. The ionospheric vertical delays and error bound GIVE estimated using Inverse Distance Weighted with Klobuchar model is presented in this paper. The results are encouraging and this model is a good contender for implementation in GAGAN System.

INTRODUCTION

Global Positioning System (GPS) is a satellite based navigation system. It provides better positional accuracy of the user worldwide at any time. GPS, in general meets the requirements of position determination at various user platforms. But, it has limited measurement accuracy due to several factors such as clock biases of GPS satellites and the receiver, ionospheric and tropospheric delays and uncorrelated receiver noise etc. Therefore, standalone GPS is not suitable for certain navigation applications, including aircraft's landing using Category-I (CAT-I) precision approach. However, the required accuracy can be achieved by augmenting the GPS. The first Space Based Augmentation System (SBAS) was initiated by USA in early-nineties for providing coverage of Continental United States (CONUS) region. This is popularly known as "Wide Area Augmentation System"(WAAS). WAAS comprises a network of wide area reference stations (WRSs), which receive and monitor the GPS signals. Data from these stations are transmitted to the Wide area Master Stations (WMSs), where the validity of the signals from each satellite is assessed and corrections are computed. The WMSs also develop ephemeris and clock information of the geo-stationary satellites (Walter et al. 1994). All these data are packed into WAAS message and is sent to the Ground Earth Stations (GESs). The GESs uplink this message on 6455.2 MHz to the Geostationary Earth Orbit (GEO) satellites that broadcast 'GPS-like' signals to the users (El-Arini et al. 1994). The European Geo-stationary Navigation Overlay System (EGNOS) is being implemented by the European Space Agency since 1996 and is expected to be operational in the year 2004–05. The Japanese MTSAT Satellite Augmentation System (MSAS) is being implemented primarily for civil aviation sector. Canadian WAAS (CWAAS) is also at the advanced stage of its implementation and is expected to be ready by 2006. Countries such as Brazil, Mexico and China are also developing their own SBAS. The Indian SBAS is being implemented jointly by Airport Authority of India (AAI) and Indian Space Research Organisation (ISRO) and is known as GPS And Geo Augmented Navigation (GAGAN). As per the directive of International Civil Aviation Organization (ICAO), every member country has to adopt Global Satellite Navigation System as a primary future system for aviation by the year 2010. Ionospheric delay, which is a function of Total electron Content (TEC), is one of the dominant errors in SBAS. Therefore, to minimize the ionospheric delay, a suitable ionospheric grid model is required for SBAS. Grid models are more accurate and reliable than analytical function based models (El-Arini, et al. 1994-95). One of the ionospheric grid models used for the WAAS is the Inverse Distance Weighted (IDW) with Klobuchar model. In this paper, delays at the Ionospheric Grid Points (IGPs), user's Ionospheric Pierce Points (IPPs) and corresponding error bound Grid Ionospheric Vertical Errors (GIVEs) using the data from Ionospheric Reference stations of GAGAN are estimated and the results are presented.

GAGAN

As a part of satellite-based communication, navigation, surveillance (CNS) and air traffic management (ATM) requirements for civil aviation in India, GAGAN is planned to meet the objectives of national satellite-based navigation system. The navigation performance parameters are accuracy, integrity, time to alert, continuity and availability over the Indian service region. The required horizontal and vertical accuracies are 16m and 6 m respectively with a confidence bound of 99.9%. (Kibe 2003). Initial study on placement of 20 ionopspheric reference stations over Indian region, is carried out (Sarma, Sasibhusana Rao, & Venkata Rao 2000). 20 TEC receivers located around geographic latitudes of 72°E, 77°E, 82°E, 88°E and 93°E over Indian region are used for collecting GPS data. The Indian master control center (INMCC) and an Indian navigation land uplink station (INLUS) are collocated at Banglore. One navigation payload on geo-stationary satellite, GSAT 4 at orbital location of 82°E longitude in the Indian Oceanic Region (IOR) is planned to meet the objectives of GAGAN. Relatively benign ionospheric conditions that exist in the mid-latitude CONUS region (USA) are compatible with the ionospheric range corrections for WAAS (Komjathy, Sparks' Mannucci, & Pi Xiaoqing 2002). The existing grid based models work well in the mid-latitude regions, where the spatial and temporal changes in the structure of the ionosphere are fairly smooth during the magnetically quiet conditions (Lejeune et al. 2002). In contrast, in countries such as Brazil and India, the low latitude and equatorial regions are known to exhibit much higher range delays due to spatial and temporal variability even during the magnetically quiet conditions. Steep spatial gradients near the anomaly peak, ionospheric scintillations and large-scale irregularities over smaller differential distances have been observed in these regions. To minimize the ionospheric delay error in the Indian region, a suitable grid-based ionospheric model is required for GAGAN. The measured TEC data from 12 channel dual frequency GPS receivers at ionospheric reference stations are obtained from SAC, Ahmedabad. The TEC data are used to obtain ionospheric corrections using IDW with Klobuchar model.

IDW Model Principle

The Klobuchar time delay model is considered with IDW model to take into account the temporal variations of the IPP delays. This model estimates the vertical delays at the selected IGP by measuring the delays of surrounding IPPs and computing their weights. According to IDW, the weight will be more to an IPP nearer to the IGP as compared to the farther IPP, which has minimum correlation or nearly no-correlation on the IGP delay. The contribution by distant IPPs is very less. Therefore, the IPPs lying within a specified maximum distance centering the IGP are only considered in the delay estimation. In case there are two IPPs equally close to the same IGP, the greater weight is given to the IPP corresponding to a satellite at higher elevation angles (Enge 1996; Chao 1997). The weight (w_i) depends on inverse of the distance from selected j^{th} IGP to the i^{th} IPP and the ratio of IGP to IPPs delays obtained using analytic ionospheric model as (Enge et al. 1996),

$$w_i = \left(\frac{\tau_j}{\tau_i}\right)\frac{\left(\frac{1}{d_{ij}}\right)}{\sum_{k=1}^{n}\left(\frac{1}{d_{kj}}\right)} \tag{1}$$

Where d_{ij} is the distance between the i^{th} IPP to the j^{th} IGP, d_{kj} is the distance between the k^{th} IPP to the j^{th} IGP, n is the number of surrounding IPPs, τ_i and τ_j are the vertical ionospheric delays at the i^{th} IPP and j^{th} IGP respectively obtained using Klobuchar time delay algorithm.

The Klobuchar time delay model provides ionospheric delay correction of the order of 50-60% (Klobuchar 1987). It may be due to application of truncated sine/cosine representation of diurnal curve and reduction in number of trigonometric calculations in the model. Therefore, the measurement IPP delay takes into account of the error in the nominal model as,

$$D_{Vi,IPP} = D_{vi}\frac{D_{no\min al,grid,j}}{D_{no\min al,i}} = \frac{\tau_j}{\tau_i}D_{Vi} \tag{2}$$

Where, D_{Vi} is the vertical delay at the i^{th} IPP as obtained from measurement, $D_{nominal,\ grid,}$ and $D_{nominal,\ i}$ are the vertical delays estimated using single frequency Klobuchar's time delay model at the j^{th} IGP and i^{th} IPP respectively.

The delay at the j^{th} IGP is the sum of products of the IPP Delays, D_{vi} and their weights, w_i as

$$D_{vj} = \sum_{i=1}^{n} D_{Vi,IPP} w_i \quad (3)$$

This equation is used to estimate vertical delays at selected IGP surrounded by nearby IPPs.

Data Processing

The GPS data obtained from SAC, Ahmedabad consists of 23 parameters. Out of the 23 parameters only 7 parameters namely SV number, week number, seconds of the week, elevation, azimuth, TEC and DTEC are considered for analysis. These are used for calculating other required parameters for estimating the delays at IGPs and user's IPPs. The data-sampling rate is 60 seconds. In this paper, single station (Jodhpur) and four stations (Ahmedabad, Delhi, Jodhpur and Bhopal) data corresponding to 4th April 2003 and 1st July 2003 are considered for time delay estimations. These data are processed and stored in a separate data file in EXCEL format. The data are sorted with respect to seconds of the week so that data corresponding to a particular epoch can be identified easily. Then, the data are used to compute the IPP locations and their vertical delays, vertical IGP delays, user's IPP delays and GIVEs at selected IGPs as described below.

Estimation of Latitudes and Longitudes of IPPs

The IPP location is determined using station location and corresponding elevation and azimuth angles. For a visible SV, the location of an IPP is shown in Fig.1. The other relevant parameters are also shown in Fig. 2.

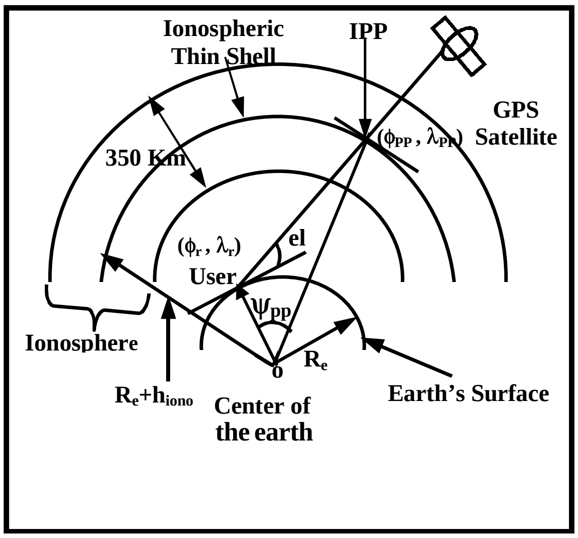

Figure 1. IPP at Point E due to a GPS SV

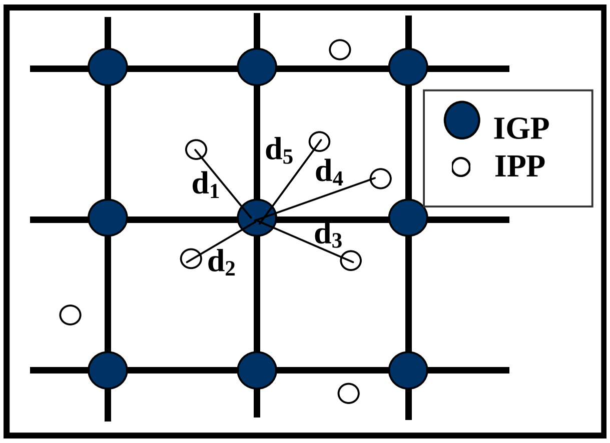

Figure 2. Multiple IPPs in Thin-Shell Model

Let (ϕ_r, λ_r) be the latitude and longitude of a reference station, el and A_z respectively be the elevation and azimuth angles of one SV observed from that station. The IPP latitude and longitude are given as (FAA 1999),

$$\phi_{pp} = Sin^{-1}\left(Sin\phi_r Cos\psi_{pp} + Cos\phi_r Sin\psi_{pp} CosA_z\right)\text{deg.} \quad (4a)$$

$$\lambda_{pp} = \left(\lambda_r + Sin^{-1}\left(\frac{Sin\psi_{pp} SinA_z}{Cos\phi_{pp}}\right)\right)\text{deg.} \quad (4b)$$

Where ψ_{pp} is the Earth angle subtended by the lines joining center of the Earth with IPP and the user location (see Fig.1). This is given as,

$$\psi_{pp} = 90 - el - Sin^{-1}\left(\frac{R_e}{R_e + h_{iono}} Cos(el)\right)\text{deg.} \quad (4c)$$

Re is the Earth's equatorial radius (6378.1Kms) and h_{iono} is the ionospheric height (350 Kms)

Estimations of IPP Delays

The GPS receiver measures the slant TEC for each visible SV. The slant IPP delay (D_{si}) is obtained from the slant TEC using the standard equation,

$$D_{si} = \frac{40.3}{cf^2} \times TEC_i \quad (5)$$

where, c is the velocity of light and f is the L_1 signal frequency (1575.42MHz). The vertical delay at an IPP (D_{vi}) can be obtained by multiplying the slant delay (D_{vi}) with a Mapping Function (MF) as,

$$D_{vi} = D_{si} \times MF \quad (6)$$

For a given ionospheric thin shell height, the most commonly used MF is (Langley et al. 2002),

$$MF = \left(1 - \left(\frac{R_e \times \cos(el)}{R_e + h_{iono}}\right)^2\right)^{-\frac{1}{2}} \quad (7)$$

The MF variation for different ionospheric thin shell ionospheric heights is shown in Fig.3.

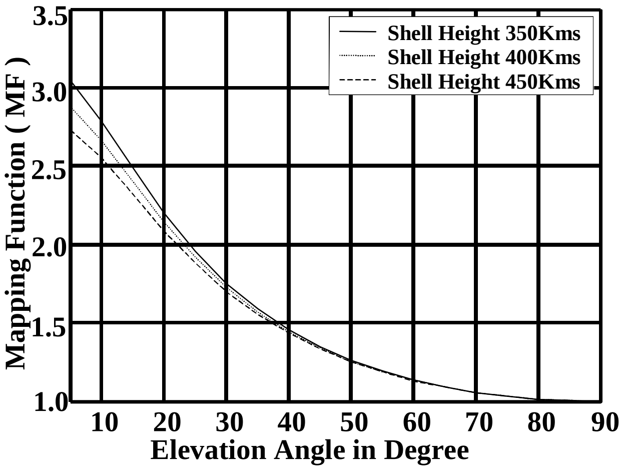

Figure 3. MF for a given ionospheric height

As seen from the figure, for a given ionospheric height of 350 Kms, the maximum value of MF at 5°elevation angle is 3.0 and decreases to 1.0 for an elevation angle of 90°. The spherical distance between selected j[th] IGP (ϕ_j, λ_j) and i[th] IPP (ϕ_i, λ_i) is computed as (Werner, Rossbach & Wolf 2000),

$$d_{ij} = 6378.1 \times Cos^{-1}[Sin\phi_j Sin\phi_i + Cos\phi_j Cos\phi_i Cos(\lambda_j - \lambda_i)] \text{ Kms} \quad (8)$$

Inverse of the distance (i.e. $1/d_{ij}$) is used in the estimation of weight to an IPP (for IGP delay estimation) and weight to a selected IGP (for user's IPP delay estimation).

ESTIMATION OF VERTICAL DELAY AT THE IGP

The expression for IGP delay can be obtained by substituting the value of IPP weight (w_i) of Eq.1 in Eq. 3. The vertical delay at the IGP for n IPPs case is as given (El-Arini, Klobuchar & Doherty 1994),

$$D_{vj} = \sum_{i=1}^{n} \left(\frac{\tau_j}{\tau_i} \right) \frac{D_{vi}\left(\frac{1}{d_{ij}}\right)}{\sum_{k=1}^{n}\left(\frac{1}{d_{kj}}\right)} \text{for } d_{ij} \neq 0 \quad (9)$$

$$= D_{vi} = \text{ for } d_{ij} = 0, \; i,k \in \{1,2,3,...,n\}$$

The IGP vertical delay estimation algorithm also considers the data-sampling rate, grid size and mapping function. The vertical ionospheric delays at i[th] IPP and the selected j[th] IGP can be computed using the Klobuchar single frequency time delay algorithm. The ionospheric time delay correction (ΔT_{iono}) is estimated as,

$$\Delta T_{iono} = DC + A \times \cos\left(\frac{2\pi(t - T_p)}{P} \right) \quad (10)$$

where DC is a constant term representing night-time delay (5ns), A is the amplitude of half cosine curve, P is the period and T_p is the constant phase at local peak period (i.e. 1400 hrs local time in sec = 50400sec). More details on this algorithm are reported elsewhere (Klobuchar 1987; Fees 1987).

Estimation of Vertical Delay at the User's IPP

The IDW with Klobuchar model can also be used to compute the delay at the user's IPP also. The user's delay model requires vertical delays at the surrounding four IGPs and their corresponding weights. The weights of the surrounding IGPs can be obtained using various interpolation techniques (El-Arini, Klobuchar & Doherty 1994). But, IDW model is used here due to its simplicity. Based on the computed user's IPP location, four surrounding IGPs are selected. The weight to a j[th] IGP, (w_j) is given as (Enge et al. 1996),

$$w_j = \left(\frac{\tau_u}{\tau_j} \right) \times \frac{\left(\frac{1}{d_{ju}}\right)}{\sum_{k=1}^{4}\left(\frac{1}{d_{ku}}\right)} \text{ for j, k } = 1, 2, 3 \text{ and } 4 \quad (11)$$

Where, d_{ju} is the distance between the j[th] IGP (ϕ_j, λ_j) to the user's IPP (ϕ_u, λ_u), τ_u is the vertical delay at user's IPP. The IGP weight (w_j) should satisfy the relation as,

$$\sum_{j=1}^{4} w_j = 1 \quad (12)$$

For each user's IPP in a square grid cell, the weights to its corresponding four IGPs are computed. The user's IPP vertical delay (D_{uv}) is estimated using IGP vertical delays as (El-Arini et al. 1994),

$$D_{vu} = \sum_{j=1}^{4} \left(\frac{\tau_u}{\tau_j} \right) \times \frac{D_{vj}\left(\frac{1}{d_{ju}}\right)}{\sum_{k=1}^{4}\left(\frac{1}{d_{ku}}\right)} \quad (13)$$

Where, D_{vj} is the vertical delay at the j[th] IGP as measured by the GPS receiver and d_{ku} is the distance from k[th] IGP to the user's IPP.

The user's IPPs considered in this paper are the ionospheric reference station IPPs data. The same TEC stations IPP data are used in obtaining user's delay error for determining GIVEs at IGPs under consideration.

Estimation of GIVE at selected IGP

There may be variations in the estimated delay at the IGP due to many error factors such as modeling error, mapping function error, measurement noise etc. These errors get translated from IPP locations to selected IGPs in the delay estimation process. Therefore, an error bound (GIVE) on such error is also generated at each IGP. GIVE is the maximum error bound that an IGP can have. The error bound can be on either side of the estimated IGP delay value. The condition to GIVE estimation is that for every IGP there should be at least 3 surrounding squares, each with at least one IPP. This refers to the sufficiency of IPP density around an IGP. The following important steps are used in GIVE computation (Conker et al. 1995),

(i) Compute residual error, e_{vi} due to estimated user's IPP delay ($\hat{D}_{vi}$) and measured IPP delay (D_{vi}) as,

$$e_{vi}(t) = \hat{D}_{vi}(t) - D_{vi}(t) \quad (15)$$

(ii) Estimate the mean ($\bar{e}_{vi}$) and standard deviation (S_{vi}) of user's IPP vertical delays respectively for m epoch (i.e. GPS time t_1 to t_m) measurements as,

$$\bar{e}_{vi} = \frac{1}{m}\sum_{k=1}^{m} e_{vi}(t_k) \text{ and } s_{vi} = \sqrt{\frac{1}{m-1}\sum_{k=1}^{m}\left(\bar{e}_{vi} - e_{vi}(t_k)\right)^2} \quad (16)$$

(iii) Estimate grid vertical absolute error bias at the surrounding four IGPs, $\hat{e}_{vj}$ from the absolute value of residual error at the i**th** user's IPP (i.e. $|e_{vi}(t_m)|$), for m epoch data using,

$$\hat{e}_{vj} = \sum_{i=1}^{n} \frac{\left(\frac{1}{d_{ij}}\right)}{\sum_{k=1}^{n}\left(\frac{1}{d_{kj}}\right)} |e_{vi}(t_m)| \quad (17)$$

(iv) Generate a conservative tolerance error bound E_{vi}, for every valid user's IPP in a surrounding square. E_{vi} is derived from a two-sided statistical tolerance interval (γ) that contains a proportion (p) of a normally distributed population over a given sample size (m) as,

$$E_{vi} = |\bar{e}_{vi}(t)| + g(\gamma; p; m)\, s_{vi} \quad (18)$$

Where, $|\bar{e}_{vi}(t)|$ is the absolute value of mean error and $g(\gamma; p; m)$ is the statistical confidence factor.

The confidence factor can be computed for given γ, p and m values (Hahn & Meeker 1991). For γ = 0.999 (i.e. 99.9%), p = 0.999 and m = 5, $g(\gamma; p; m)$ is 23.54 and for m=30 it is 5.43. It decreases with the number of GPS data samples.

(v) GIVE at j[th] IGP is the sum of ($\hat{e}_v$) the maximum tolerance error bound [$\max_k(E_{vk})$] and an allowance for vertical ionospheric delay quantization (q_u) at the elected IGP as,

$$GIVE_j(IGP) = \hat{e}_{vj} + \max_k(E_{vk}) + q_u/2 \quad (19)$$

Where, q_u = 0.0625m.

The confidence factor (E_{vk}) in GIVE term is due to spatial decorrelation of GPS data obtained at the TEC stations. GIVE and statistical tolerance bound are determined at the places where data exists. However, it can be estimated at places where there is no data, at decrease in tolerance interval (γ < 0.999). This indicates that the GIVE at the selected IGP is estimated with a confidence bound lesser than required value of 99.9%.

RESULTS AND DISCUSSIONS

An algorithm is developed to estimate the vertical delays and GIVEs. The inputs to the algorithm are data from multiple reference stations, Klobuchar coefficients, size of the square grid, IGP locations, length of epochs and statistical confidence factor for a given tolerance interval. The confidence factor $g(\gamma; p; n)$ is selected on the basis of number of epochs considered in the data analysis. The output of the developed algorithm are IGP delays, GIVEs and users IPP delays.

IGP Delay Estimation Results

Using the Jodhpur reference station data corresponding to a typical day (4[th] April' 2003), the vertical delays at the IPPs for eight visible SVs (6, 9, 14, 15, 17, 18, 23 and 26) are calculated. The data time particulars are : GPS week number 1212 and seconds of the week (SOW) 473100 seconds. This corresponds to local time (LT) of 16:55 Hrs. The vertical delays τ_i, τ_j, D_{vi}, and the distance d_{ij} are computed for all the visible SVs. The IGP delay, D_{vj} estimated at the selected IGP (25°N, 75°E) is 43.92nsec (13.17m). The IPPs and IGP locations are shown in Fig.4.

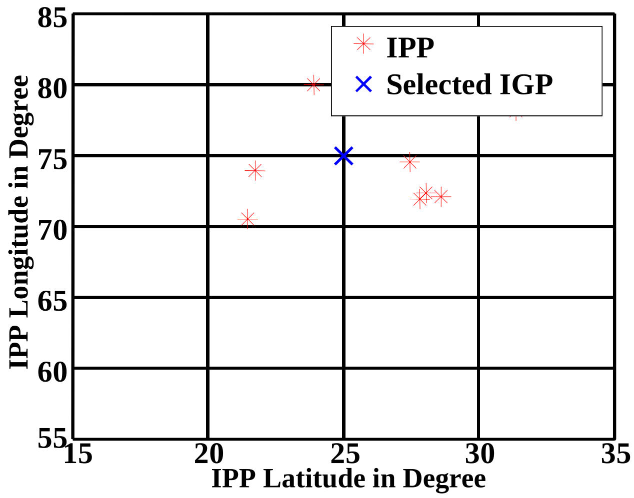

Figure 4. IPPs and selected IGP (25°N, 75°E) at 16:55Hrs

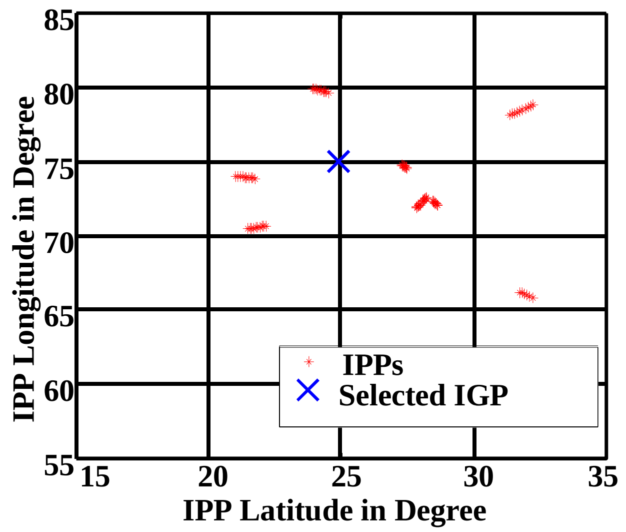

Figure 5. IPPs Tracks for 5 epochs GPS data from 16:55 Hrs to 17:00 Hrs

Similarly, the estimated vertical delay at the same IGP at the next epoch (after 60 seconds from SOW 47160 sec) is 43.97 nsec (13.19m). The variation on the estimated delay at the IGP is 0.05nsec (0.02m) for one epoch duration.

As the GPS SVs are orbiting around the Earth, their locations vary forming IPP tracks with time. The tracks of typical 8 IPPs around the selected IGP for 5 epochs duration of GPS data are shown in Fig. 5.

It is observed from the two consecutive epochs that the IGP delays do not vary appreciably. The difference in estimated vertical delay at these two epochs is 0.04nsec, which is negligible. The estimated vertical delay at the same IGP for the same satellites after 5 epochs is 42.10nsec (12.6m), showing a variation of 1.82nsec (0.57m).

Table 1. User's Interpolated IPP delay for GPS SV 6

S.No.	IGP (Lat./Lon.) (°)	IGP Delay (in nsec)	IGP Weight	User's IPP (Lat./Lon) (in °)	Interpolated Delay at user's IPP
1.	20°E, 70°N	38.92	0.2933	21.7328°E, 73.8704°N	37.17ns (11.25m)
2.	20°E, 75°N	36.97	0.3624		
3.	25°E, 75°N	43.92	0.1977		
4.	25°E, 70°N	37.05	0.1467		

User's IPP Delay Estimation Results

The inputs to the user's IPP Estimation algorithm are user's location input, elevation and azimuth angles of GPS SV and IGP delays. Based on the user's IPP location, the algorithm selects corresponding four IGPs encircling the user's IPP. The weights and the delay are computed using Eqns. 11&9 respectively. The location of the grids with their computed weights and vertical delays and user IPP locations for GPS SV 6 are presented in Table 1.

The interpolated delay at the user's IPP is 37.17 nsec (11.15m) (4th April'2003, LT 16:55 Hrs). It is evident from the Table that the estimated vertical delay at the user's IPP (21.7328°E, 73.8704°N) is approximately equal to the vertical delay at the nearest IGP (20°E, 75°N). This is due to the user's IPPs proximity to that particular IGP. This results to more influence of the IGP on the estimated user's IPP delay. The locations of user's IPP and selected 4 IGPs in the cell for SV 6 are presented in Fig. 6.

The developed algorithms for the estimation of various parameters for single station are proved to be reliable; these are extended to multiple TEC station data.

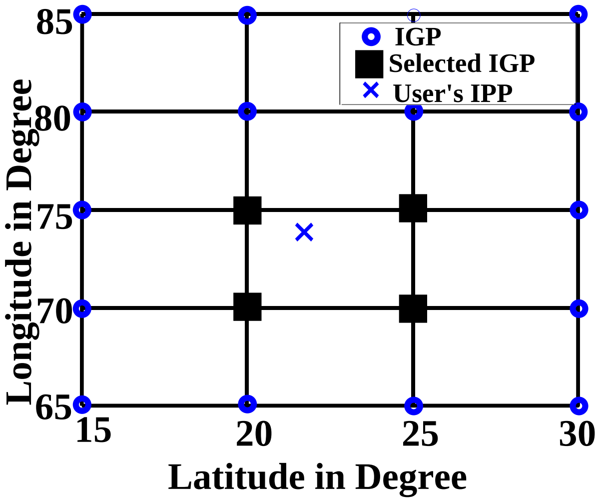

Figure 6. User's IPP with surrounding 4 IGPs for GPS SV 6

IGP delay, User IPP Delay and GIVE Estimation Results for Multiple Reference Stations

Four stations namely Ahmedabad, Delhi, Jodhpur and Bhopal are considered for the data analysis. Initially, the IPP locations are computed. This information is used for selecting the IGPs. The IPPs and IGPs locations are shown in Fig. 7.

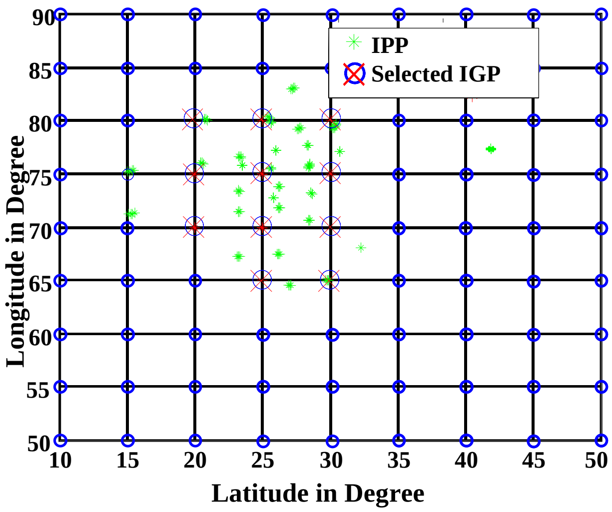

Figure 7. IPPs/ IGPs Locations for 4 Multiple Reference Stations data

It is obvious from the figure that 11 IGPs are selected by the algorithm from 32 IPPs. For selection of an IGP, it is necessary that there must be at least three surrounding squares cells, each with at least one IPP. Such selected IGPs are also called as valid IGPs. The estimated vertical delays at all selected IGPs with their error bounds (GIVEs) are presented in Table 2.

Table 2. IGP Delay and GIVE Results for four Multiple Stations

S.No.	IGP Latitude & Longitude	IGP Delay (m)	GIVE (m)
1	20°N 70°E	4.9440	1.1076
2	20°N 75°E	5.0339	1.1167
3	20°N 80°E	4.8700	1.0996
4	25°N 65°E	5.2678	1.1048
5	25°N 70°E	5.0759	1.1576
6	25°N 75°E	5.0478	1.2011
7	25°N 80°E	5.1864	1.2163
8	30°N 75°E	5.4503	1.3136
9	30°N 80°E	5.5872	1.2493
10	30°N 75°E	4.9417	1.2351
11	30°N 80°E	5.6389	1.2317

It is observed from Table 2 that the maximum bound on the vertical delay at each IGP is less than 2.0m, which is within the limit specified for GIVE in CONUS region for quiet period (Conker 1995; Walter, Enge & Hansen 1997). The minimum GIVE is 1.1048m at IGP (25°N 65°E) and the maximum GIVE is 1.3136 at another IGP (30°N 75°E). The difference in GIVE is 0.21m, which shows spatial correlation on the error bounds for all surrounding IGPs.

The user's IPP for which there are four valid IGPs (with known delays) encircling the IPP are called valid user's IPPs. On this basis, the user's IPP delay algorithm is used to find 17 valid user's IPPs. The estimated vertical delays at various user's IPPs are compared with their corresponding measured IPP delays and are presented in Table 3.

It is evident from Table 3 that the maximum difference in the estimated user's IPP delay is about 0.7m. The variations in the estimated delays are due to selected grid size, modeling of mapping function errors. Optimizing the MF used in the model can further reduce the error. The reduction in grid size increases the accuracy of the user's delay estimation. But the availability of grid delays around the user's IPP decreases with size reduction. Therefore, the grid size is required to be optimized taking into account of IPP density data.

Table 3. Estimated Users IPPs Delays for Four multiple stations

S.No.	User's IPP Latitude (°)	User's IPP Longitude (°)	User's IPP Measured delay (m)	User's IPP Estimated delay (m)	Estimation Error (m)
1.	23.7605	71.6714	4.0851	4.7860	+0.7009
2.	22.6837	73.5520	4.4517	4.7949	+0.3432
3.	25.3114	76.3108	4.3121	4.8494	+0.5372
4.	25.6716	73.3856	4.9438	4.8776	-0.0662
5.	27.3885	70.1222	4.3220	4.6152	+0.2932
6.	28.9258	75.9023	4.4188	4.6248	+0.2060
7.	27.7902	77.8351	4.2063	4.6672	+0.4608
8.	21.3584	75.5416	4.2971	4.6979	+0.4008
9.	24.0074	76.0583	5.3066	4.6743	-0.6323
10.	25.8125	77.8442	4.6360	4.7564	-0.1204
11.	25.2318	67.1903	5.3137	4.6741	-0.6396
12.	26.7283	72.0567	4.2265	4.4931	+0.2666
13.	25.6477	73.9769	4.6527	4.8414	+0.1887
14.	28.1475	76.6955	4.2200	4.8488	+0.6288
15.	21.9169	77.2577	4.3429	4.9050	+0.5621
16.	28.5229	73.8100	4.9898	4.9355	-0.0543
17.	28.4971	65.0313	4.2164	4.9168	+0.7004

CONCLUSIONS

The IDW model is a spatial interpolation technique, which can be used for the estimation of ionospheric vertical delays at the selected IGPs and user's IPPs. Relevant software is developed and tested. The vertical delays at selected IGPs due to a single reference station (Jodhpur) and multiple reference stations (Ahmedabad, Delhi, Jodhpur and Bhopal) are estimated. The modeled vertical delays accuracy depends on the density of IPPs around an IGP, grid size and the data update rates. The estimated user's IPP delays for multiple stations data agree with the measured IPP delays. This model is simple and expected to be reliable for ionospheric grid model over GAGAN.

ACKNOWLEDGEMENTS

Thanks are due to Dr. B.M. Reddy, INSA Scientist, NGRI, Hyderabad and Dr. D.R. Lakshmi, Emeritius Scientist, NERTU, OU, Hyderabad for their valuable suggestions in improving the quality of this paper. The work presented in this paper is sponsored by the Space Application Center (SAC), Ahmedabad, ISRO, Govt. of India under the Project entitled, "Development of Grid-based Ionospheric Model for Indian WAAS", vide Order No. SAC-OU-MOU-(IONO.MOD.)-2003 dated 31-03-2003.

REFERENCES

Chao, Y.C., 1997. Ionospheric algorithm for WADGPS, Ph.D Thesis, Stanford University, USA.

Conker R.S., El-Arini, M.B., Albertson, T.W., Klobuchar, J. & Doherty P. H., 1995. Development and Assessment of Real-Time Algorithms to Estimate the Ionospheric Error Bounds for WAAS, Navigation Journal 44 (1), 77-87.

El-Arini, M.B., Klobuchar, J.A. & Doherty, P.H., 1994. Evaluation of the GPS Wide Area Augmentation System (WAAS) Ionospheric Grid Algorithm during the Peak of Current Solar Cycle, Proceedings of 1994 National Technical Meeting (NTM), San Diego, CA, January 24-26, 961-68.

El-Arini, M.B., Conker R., Albertson, T.W., Reagan J.K., Klobuchar, J.A. & Doherty P. H., 1994-95. Comparison of Real-Time Ionospheric Algorithms for a GPS Wide-Area Augmentation System (WAAS), Navigation: Journal of the Institute of Navigation, ION, 44 (4), 393-413.

Enge P., Walter T., Kee C., Chao Y.C. & Tsai Y.J., 1996. Wide Area Augmentation of the Global Positioning System, Proceedings of the IEEE, 84 (8), 1063-88.

U.S. Department of Transportation, Federal Aviation Administration, 1999. Wide Area Augmentation System (WAAS), FAA-E-2892B, Change 1, DTFA01-96-C-00025, 2-35 to 2-36.

Fees, W.A., 1987. Evaluation of GPS Time Delay Model, IEEE Transaction on Aerospace and Electronic System (AES), 23(3), 332-338.

Hahn G.J. and Meeker, W. Q., 1991. "Statistical Intervals: A Guide for Practioners", John Wiley & Sons, Inc., New York.

Kibe, S.V., 2003. Indian plan for Satellite-based navigation system for civil aviation, Curr. Sci., . 84 (11), 1405-11.

Komjathy A., Sparks L, Mannucci A. J. & Pi X, 2002. An Assessment of the Current WAAS Ionospheric Correction Algorithm in the South American Region, Proceedings of the Institute of Navigation GPS 2002, 24-27 Sept., Portland, OR, USA, 1286-1295.

Klobuchar, J. A.,1987. Ionospheric time delay Algorithm for single frequency GPS users, IEEE Transaction on Aerospace and Electronic System (AES), 23 (3), 325-331.

Langley R., Fedrizzi M., Paula E., Santos M. & Komjathy A., 2002. Mapping the low latitude Ionosphere with GPS, GPS World, 13 (2), 41-46.

Lejeune R., El-Arini M. B., Klobuchar J.A. & Doherty P.H., 2002. Adequacy of the SBAS Ionospheric Grid concept for Precision Approach in the Equatorial Region, Proceedings of the Institute of Navigation, ION-GPS 2002, Portland OR, USA, 1330-1349.

Sarma, A.D., Sasi Bhushana Rao, G. & Venkata Rao, V., 2000. Ionospheric Reference Station Placement for INWAAS: A Preliminary Study", J. Ind. Geo. Uni., 4, 41-49.

Walter, T. C., Kee, C., Chao, Y.C., Tsai, Y.J., Peled, U., Ceva, J. Barrows, A.K., Abbott, E., Powell, D., Enge, P. & B. Parkinson, 1994. Flight Trials ofWide Area Augmentation System (WAAS), Proceedings of ION, GPS-1994, Salt Lake City, Utah, 1537-46.

Walter, T., Enge, P., & Hansen, A., 1997. A proposed integrity Equation for WAAS MOPS, the Institute of Navigation (ION) GPS, 475-484.

Werner W., Rossbach U. & Wolf R., 2000. Algorithms and Performance of EGNOS CPF Independent Check Sets, Proceedings of the Institute of Navigation (ION), GPS 2000, 219-229.

(Accepted 2004 April 30. Received 2004 April 4; in original form 2004 January 28)