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Global Positioning System L-Band Signal Code Delay Estimation for Single Frequency GPS/GNSS Services

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Abstract: ***GPS/GNSS satellites continuously radiate L-band signal towards the earth and are being affected by the ionospheric propagation medium in different ways. The more predominant and irremovable GPS signal C/A code delay error due to the ionosphere (i.e. ionospheric time delay) causes faults in pseudo range measurements. This is a serious problem for single frequency users of low latitude regions. Hence, this paper focuses on estimation and study of ionospheric time delay irregularities over low latitude International GNSS services(IGS) receiver stations namelyPBRI (lat/lon: 11.64° N/92.71° E),IISC (lat/lon: 13.02° N/77.57° E), HYDE (lat/lon: 17.41° N/78.55° E) and LCK4 (lat/lon: 26.91° N/ 80.96° E). Theionosphericticme delay irregularities estimated with Klobuchar algorithm which is being used in single frequency GPS receivers are compared with experimentally measured time delay by computing a parameter called percentage of deviation (PD). This research work has been carried out for autumn equinox (SEPTEMBER and OCTOBER) period of High Solar Activity (HSA) and Low Solar Activity (LSA) years (2014 and 2008). The maximum delayestimated due to experimental data and Klobuchar algorithm is 51.36ns and 36.95ns respectively. The mean deviation of Klobuchar algorithm estimated time delay from experimental data is maximum (42.77%) for the HSA year (2014)at the LCK4 station. The minimum mean deviation is 27.42% for the LSA year (2008) at IISC station. The results would be helpful in improving of Klobuchar algorithm. So that the accuracy of single frequency receiver improves.***

Keywords: **GPS, IGS, ionospheric time delay and Klobuchar algorithm.**

I. INTRODUCTION

Global Navigation Satellite System (GNSS) is a satellite based navigation system which provides continuous position and navigation services for the single and dual frequency user globally. It comprises Global Positioning System (GPS) developed by the department of defence United States, GLONASS of Russia, COMPASS Navigation Satellite System (CNSS) of China and GALILLEO of European Union (EU). For all these systems satellites constellation was placed at the height of MEO and above (GSO/GEO). When a GPS or other constellation satellite broadcast signal towards the earth on (1-2 MHz) band frequency, it is being delayed in the ionosphere medium due to the presence of free electrons produced by the Sun's Ultra Violet ionization effect. The total number of free electrons produced in 1 meter^2 volume is called Total Electron Content (TEC) and it introduces error in pseudorange measurements [1]. Since, the ionosphere is a dispersive medium TEC can be measured by using pseudo ranges of two GPS frequencies L1 (1575.42 MHz) and L2 (1227.60 MHz) as given below [2].

$$TEC = \frac{1}{40.3}\frac{L_1^2 L_2^2}{(L_1^2 - L_2^2)}(P_1 - P_2)$$

$$P_1 = \rho + d_\rho + c(dt - dT) + d_{trop} + TD_1 + \varepsilon_{mp,p,1}$$

$$P_2 = \rho + d_\rho + c(dt - dT) + d_{trop} + TD_2 + \varepsilon_{mp,p,2}$$

(1)

Where Pf (f=1,2) is the code pseudo range measurements of L1 and L2, ρis true range, $d_\rho$is satellite orbit error, c is the speed of light (3*10^8 m/sec), dt, dT are satellite and receiver clock offset errors, d_{trop} is the tropospheric delay, TD is the ionospheric time delay, $\varepsilon_{mp,p,f}$ are multipath and receiver noises. The corresponding ionospheric time delay (in Nano seconds),

$$TD = \frac{40.3.TEC}{cL^2} \quad (2)$$

As, the ionospheric time delay is a serious problem for the single frequency users over the low latitude regions like India. The continuing studies are needed to understand and predict its behaviour. Several models such as Klobuchar, NeQuick and International Reference Ionosphere (IRI) are developed for correcting the ionospheric time delay [3], [4], [5]. Also, it was reported that the ionospheric time delay effect can be reduced from 26.13% to 6.4% using IRI-2007 model with respect to the Klobuchar algorithm over the low latitude region during spring and autumn seasons of low solar activity year [6]. A new method "Orthogonal decomposition algorithm" is proposed for estimating and correcting the ionospheric time delay [7]. Ningbo Wang et al., proposed a method

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to improve single frequency GPS ionospheric time delay measurements [8]. The present paper reports the irregularities of ionospheric time delay error and comparison with Klobuchar model over four IGS stations namely PBRI, IISC, HYDE and LCK4 during autumn equinox period of LSA and LSA years (2008 and 2014). The results obtained at selected stations are useful to understand time delay irregularities and the improvement of Klobuchar algorithm.

II. KLOBUCHAR ALGORITHM

This algorithm was developed by John A. Klobuchar and published a paper in the year 1987 to estimate the ionospheric time delay of the GPS L1 frequency signal. In this algorithm day time delay is represented bythe positive partof the cosine function and night time delay is constant of 5ns [3].

$$TD = \begin{cases} F \times \left[5 \times 10^{-9} + \sum_{n=0}^{3} \alpha_n \emptyset_m^n \times \left(1 - \frac{x^2}{2} + \frac{x^4}{24}\right)\right], daytime \\ 5 \times 10^{-9}, \quad nighttime \end{cases}$$

Where, $x = \frac{2\pi(t-50400)}{\sum_{n=0}^{3} \beta_n \emptyset_m^n}$(3)

Where TD= ionospheric time delay (nanosec), F = slant factor and its expression is presented in eqn. (11)α_n and β_n are coefficients.

Since the daytime delay is cosine function, its amplitude and period of the cosine function are given as,

$$a_m = \sum_{n=0}^{3} \alpha_n \emptyset_m^n \qquad (4)$$

$$P_d = \sum_{n=0}^{3} \beta_n \emptyset_m^n \quad (5)$$

Where, a_m is the amplitude and P_d is the period of the cosine function. $\emptyset_m$ is the Geo magnetic latitude and is given as,

$$\emptyset_m = \emptyset_{sub-lat} + 0.064\cos(\lambda_{sub-long} - 1.617) \quad (6)$$

Where, $\emptyset_{sub-lat}$ and $\lambda_{sub-long}$ are subionospheric latitude and longitudes and their expressions are given below. The geometry used for these measurements is shown in Fig1.

$$\emptyset_{Sub-lat} = \emptyset_u + \Psi_E \cos A \quad (7)$$

$$\lambda_{Sub-long} = \lambda_u + \frac{\Psi_E \sin A}{\cos \emptyset_{Sub-lat}} \quad (8)$$

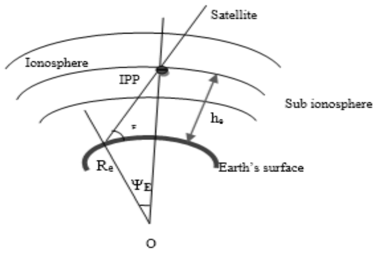

Fig1: Geometry of sub-ionospheric point

Where, Ψ_E is the earth angle defied as the angle betweenthe radius of the earth (R_e) and subionospheric point radius. E is elevation angle and h_e is height of the sub-ionosphere (350 kms). This model assumes that the total ionosphere is placed at a height of 350 kms.

$$\Psi_E = \frac{0.0137}{E+0.11} - 0.022 \quad (9)$$

Local time (t) can be computed as.,

$$t = 4.32 \times 10^4 \lambda_{Sub-long} + GPS\ time\ (sec) \quad (10)$$

Slant factor (F) is given as,

$$F = 1.0 + 16.0 \times (0.53 - E)^3 \quad (11)$$

Further, the step-by-step procedure is explained with the help of the flowchart (Fig 2).

III. TIME DELAY ESTIMATION WITH EXPERIMENTAL DATA

GPS data of HSA (2014) and LSA (2008) years autumn equinox for considered stations are collected from the SOPAC (Scripps Orbit and Permanent Array Center) which serves as global analysis centre for International GNSS services (IGS) networks. Then, SOPAC provided hatanaka data format is converted into Receiver Independent Exchange (RINEX) format. TEC is estimated using pseudo ranges measured on both L1 and L2 (i.e. P1 and P2) frequencies for all the available satellite signals using eqn. (1). The details of considered stations with coordinates and data availability in an autumn equinox period of both LSA and HAS years are presented in Table I & II. Further, the ionospheric time delay estimated with single frequency GPS receiver model (Klobuchar algorithm) is evaluated by computing a parameter called percentage of deviation (PD).

$$PD = \frac{Experimental - Model}{Experimental} \times 100 \qquad (12)$$

Table I. IGS receiver stations coordinates and data availability for LSA (2008) year autumn equinox

Receiver stations	Geo Graphic Latitude	Geo Graphic Longitude	Geo Magnetic Latitude	Geo Magnetic Longitude	Days Considered (No. Of Days)
					Autumn season
IISC	13.02°N	77.57°E	4.27°N	150.53°E	53
HYDE	17.41°N	78.55°E	8.54°N	151.86°E	52

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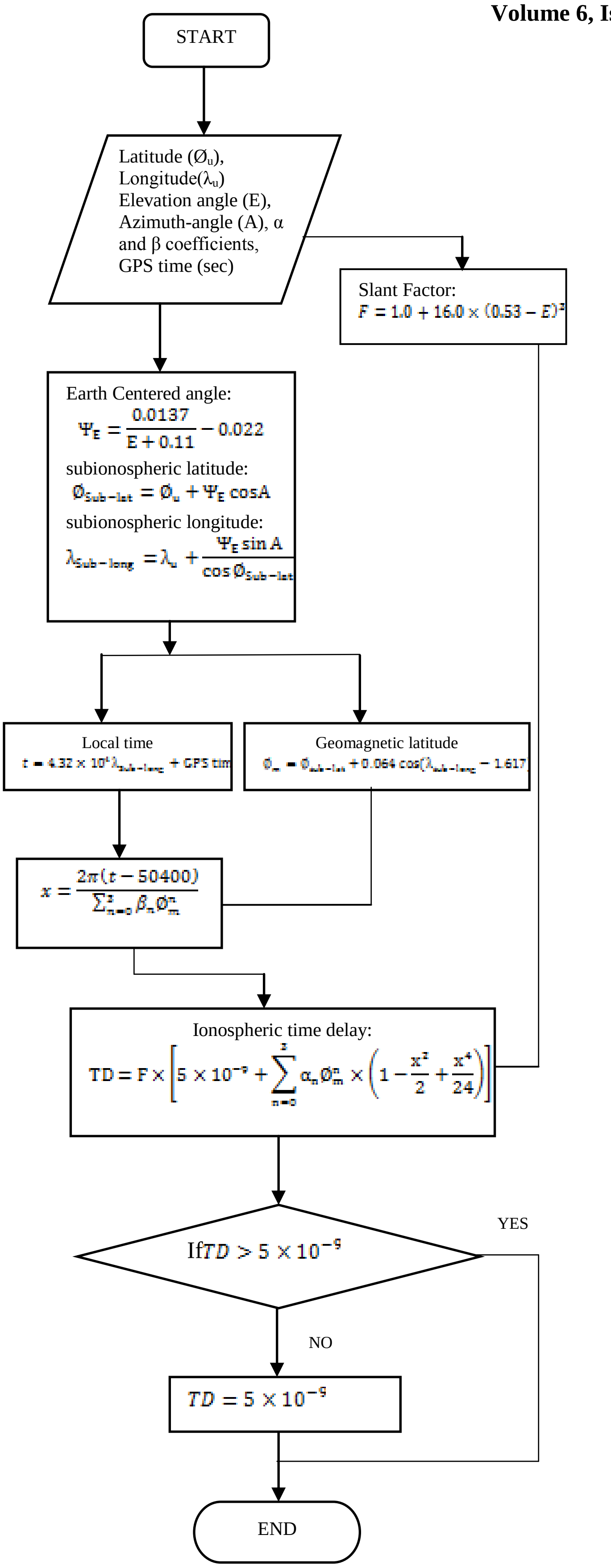

Fig 2: Flowchart of various steps involved in Klobuchar algorithm

Table II. IGS receiver stations coordinates and data availability for HSA (2014)year autumn equinox

Receiver stations	Geo Graphic Latitude	Geo Graphic Longitude	Geo Magnetic Latitude	Geo Magnetic Longitude	Days Considered (No. Of Days) Autumn season
PBRI	11.64° N	92.71° E	2.13° N	165.55° E	57
IISC	13.02° N	77.57° E	4.45° N	150.85° E	26
HYDE	17.41° N	78.55° E	8.72° N	152.16° E	53
LCK4	26.91° N	80.95° E	17.96° N	155.24 °E	27

IV. EXPERIMENTAL RESULTS AND DISCUSSION

This section describes ionospheric time delay results obtained due to experimental and Klobuchar algorithm at selected stations for the equinox period (SEPTEMEBR and OCTOBER) of different solar activity periods (2008 and 2014). For better understanding, first the ionospheric time delay is estimated for a typical day in each year which is having high geomagnetic effect MARCH 27, 2008 ($3 \leq K_p \leq 5$) and SEPTEMBER 12, 2014 ($2 \leq K_P \leq 6$) and the results presented for the equinox period. MARCH 27, 2008. Fig 3 represents the ionospheric time delay profile for a typical day MARCH 27 of LSA year (2008) at the Hyderabad IGS station.In this plot red color line indicates ionospheric time delay due to Klobuchar algorithm and blue color line indicates experimental data.

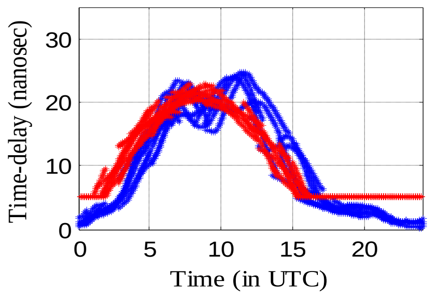

Fig 3: Ionospheric time delay profile at HYDE on MAR 27, 2008

From this, the maximum ionospheric time delay of the L1 signal measured is 24.64ms. Moreover, the ionospheric time delay value is varying with time during the day and night times. The ionospheric time delay is also estimated by the Klobuchar algorithm for the same signal and compared with experimental results. It is noticed that the peak delay due to Klobuchar algorithm (i.e. 22.88ns) is low compared to peak due to experimental data. Further, night time delay considered (i.e.5ns) in the algorithm is higher than that of measured. SEPTEMBER 12, 2014

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Fig 4 shows ionospheric time delay profiles for SEPTEMBER 12, 2014 over HYDE IGS station. The maximum ionospheric time delay values due to Klobuchar algorithm and experimental data are 37.07ns and 51.37ns respectively. Also, fluctuationsin experimental data time delay plot during the day time are more. It is observed that the time delay value is largefor the HSA year (2014) when compared to the LSA year (2008).

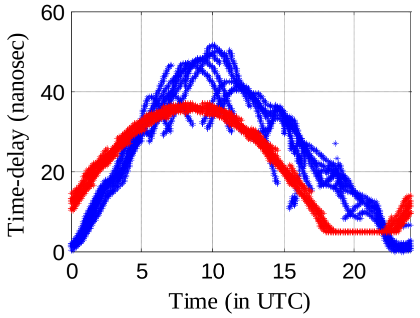

Fig 4: Ionospheric time delay profileat HYDE on SEP 12, 2014

The same time delay estimation procedure is extended for the period of equinox.

TIME DELAY ESTIMATION FOR EQUINOX PERIOD

In this section, ionospheric time delay is measured for autumn equinox period of both LSA and HSA years. The mean of Sun Spot Number (SSN), Kp and Ap are 4.16, 11.48, 6.94 for LSA. The corresponding values for HSA year are 113.35, 12.99, and 7.72. The details of time delay variations are presented below.

LOW SOLAR ACTIVITY YEAR (2008)

Figs 5-6 represents daily mean ionospheric time delay during the equinox period (SEPTEMBER and OCTOBER) of LSA year (2008) at HYDE and IISC stations and Figs 7-8 are deviation of Klobuchar algorithm from experimental data.

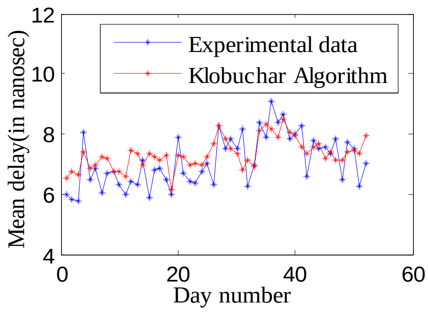

Fig 5: Daily mean ionospheric time delay at HYDE station during autumn equinox of LSA (2008)

Mean delay fluctuations are high in intensity for measured delays using experimental data than that of Klobuchar model. Daily mean delay is high (8.46ns) for the day 38 at Hyderabad IGS station. Daily mean delay of experimental data is close to Klobuchar model at IISC station compared to HYDE station.

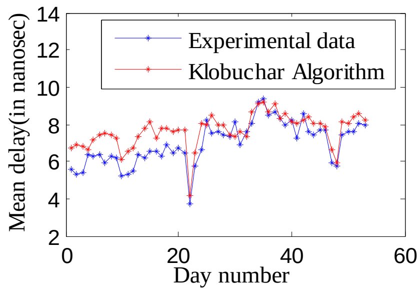

Fig 6: Daily mean ionospheric time delay at IISC station during autumn equinox of LSA (2008)

Figs 7-8 shows the klobuchar model estimated mean delay profiles deviation from the experimental values at HYDE and IISC stations. The maximum and minimum mean deviations 2.88 ns and 0.12 ns are occurred on 36 (13-10-2008) and 27 (3-10-2008) days at HYDE station. The corresponding values at IISC station are 2.27 ns and 0.11 ns for the days 41 (19-10-2008) and 38 (16-10-2008).

The fluctuations in mean delay deviation indicate that Klobuchar model performance is not uniform for all the days. For most of the days it is in between 2ns and 3 ns at HYDE station.

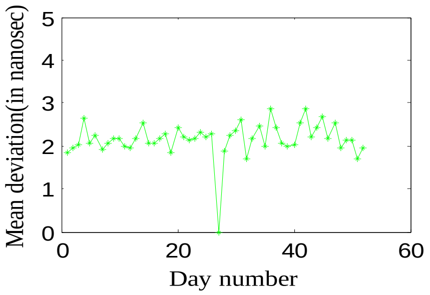

Fig 7: Mean deviation at HYDE station for the autumn equinox of LSA year (2008)

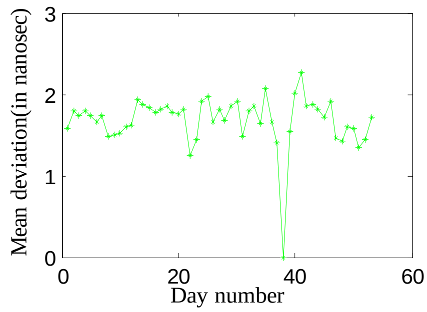

Fig 8: Mean deviation at IISCStation for the autumn equinox of LSA year (2008)

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However, the mean deviation is in between 1ns and 2 ns for IISC receiver station. It is found that the time delay deviation is more at HYDE (31.91%) (Table III).

Table III. Percentage of deviation of Klobuchar algorithm estimated ionospheric time delay from Experimental data for autumn equinox period of LSA year (2008)

Stations	Mean delay (nano sec)		Percentage Of Deviation (PD)
	Experimental Data	Klobuchar Algorithm	
IISC	6.98	7.64	27.42
HYDE	7.09	7.32	31.91

From this, it is clear that the Klobuchar model can reduces ionospheric time delay effect on GPS L1 signal up to 68.09% at HYDE station and 72.58% at IISC station during autumn equinox period of LSA year (Table III).

HIGH SOLAR ACTIVITY YEAR (2014)

In this section, the ionospheric time delay is estimated with Klobuchar model and compared with experimental data at four IGS stations namely and PBRI, IISC, HYDE and LCK4 for autumn equinox period of HSA year (2014). The maximum daily mean ionospheric time delay due to Klobuchar algorithm at PBRI, IISC, HYDE and LCK4 stations are 27.55ns, 27.67ns, 25.38ns and 19.68ns respectively for the days 27 (29-9-2014), 23 (30-10-2014), 24 (30-9-2014) and 3(19-9-2014). Likewise the maximum daily mean delays measured experimentally at considered stations are22.6ns, 23.08ns, 25.66ns and 18.89ns respectively for the days 53 (27-10-2014), 22 (28-10-2014), 9 (9-9-2014) and 19 (23-10-2014). The deviation of klobuchar algorithm estimated delay from experimental data is maximum (42.77%) at LCK4 (Table IV).

Table IV. Percentage of deviation of Klobuchar algorithm estimated ionospheric time delay from Experimental data for autumn equinox period of HSA year (2014)

Stations	Mean delay (nano sec)		Percentage Of Deviation (PD)
	Experimental Data	Klobuchar Algorithm	
PBRI	18.37	22.93	33.08
IISC	17.27	21.34	37.28
HYDE	19.42	20.70	38.32
LCK4	13.05	16.49	42.77

V. CONCLUSION

The ionospheric time delay of GPS L1 signal code causes biases in range measurements. As a result, users get inaccuratenavigation, position and time information. To minimize this ionospheric time delay effect, exact estimation is necessary. In this paper, GPS signal code delay is estimated using Klobuchar algorithm and compared with experimental measurements. This work is done for autumn equinox period of both LSA year (2008) and HSA year (2014) at four different stations PBRI, IISC, HYDE and LCK4.The percentage of deviation of klobuchar algorithm from experimental measurements is high (42.77%) at LCK4 station in the year 2014. Therefore, theionospheric time delay effect on single frequency GPS users can be reduced 57.23-72.58% using Klobuchar algorithm.

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