Performance Impact of Ionospheric and Tropospheric Corrections of User Position Estimation Using GPS Raw Measurements

Enik Shytermeja[1], Alban Rakipi[1], Shkëlzen Cakaj[2], Bexhet Kamo[1], and Vladi Koliçi[1]

[1] Faculty of Information Technology (FTI), Polytechnic University of Tirana, Tiranë, Albania
`{eshytermeja,arakipi,bkamo,vkolici}@fti.edu.al`
[2] Post and Telecommunication of Kosovo (PTK), Prishtinë, Kosovo
`shkelzen.cakaj@fulbrightmail.org`

Abstract. Global Positioning Systems (GPS) refers to satellite-based radio-positioning systems and time-transfer systems that provide three-dimensional course, position, and time information to suitably equipped users. At present, GPS system is world-wide used for positioning and navigation, attracting great attention from the scientific, professional and social community.GPS satellites are orbiting Earth at altitudes of 20.200 km and the GPS signal is mostly affected by the atmospheric effects. The scope of this paper is to investigate the performance impact of the atmospheric correction models in the overall positioning accuracy. Real GPS measurements were gathered using a single frequency receiver and post–processed by our proposed innovative adaptive LMS algorithm. We integrated Klobuchar and Hopfield correction models enabling a considerable reduction of the vertical error.

Keywords: GNSS systems, GPS raw measurements, Ionosphere, Troposphere, Klobuchar model, TEC, Hopfield model, PVT algorithm, VDOP.

1 Introduction

The Global Navigation Satellite Systems (GNSS) technique has evolved to become the most widely available positioning tool used by both civilians and scientists [1].

GPS is a satellite-based navigation radio system which is used to verify the position and time in space and on the Earth [2].The GPS satellites are orbiting the Earth at altitudes of about 20.200 km and it is generally known that the atmospheric effects on the GPS signals are the most dominant spatially correlated biases. The atmosphere causing the delay in GPS signals consists of two main layers: ionosphere and troposphere [3].

The Ionosphere is the band of the atmosphere from around (50 – 1000 km) above the earth's surface and is highly variable in space and time, with certain solar-related ionospheric disturbances [4]. Ionosphere research attracts significant attention from the GPS community because ionosphere range delay on GPS signals is a major errosource in GPS positioning and navigation. The ionospheric delay is a function of the

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total electron content (TEC) along the signal path and the frequency of the propagated signal, mostly affecting the vertical component of user's position (VDOP). There are different statistical model available for the correction of ionospheric range error in single frequency applications. However we can distinguish two of them such as: the Klobuchar model for GPS [5] or the NeQuick model [6] foreseen for use in European GALILEO system. In our algorithm we employed the widely used Klobuchar model because of its simple structure and convenient calculation.

The troposphere is the band of the atmosphere from the earth's surface to about 8 km over the poles and 16 km over the equator [7]. The tropospheric propagation delay is directly related to the refractive index (or refractivity). The signal refraction in the troposphere is separated into two components: the dry and the wet component, where the dry or hydrostatic component is mainly a function of atmospheric pressure and gives rise to about 90% of the tropospheric delay.

There are different mathematical models that can be used to correct the tropospheric error such as Saastamoinen and Hopfield Model [8].In verifying the effects of relative tropospheric delay in user's position estimation, we employed the most common and precise method, called Hopfield correction model.

In the next section, we will investigate in details the impact of Klobuchar and Hopfield model for ionospheric and tropospheric errors respectively, implemented in our algorithm in post-processing mode. Therefore, the recording of the observed satellite-to-receiver pseudoranges is required and this is achieved from the use of a single frequency receiver.

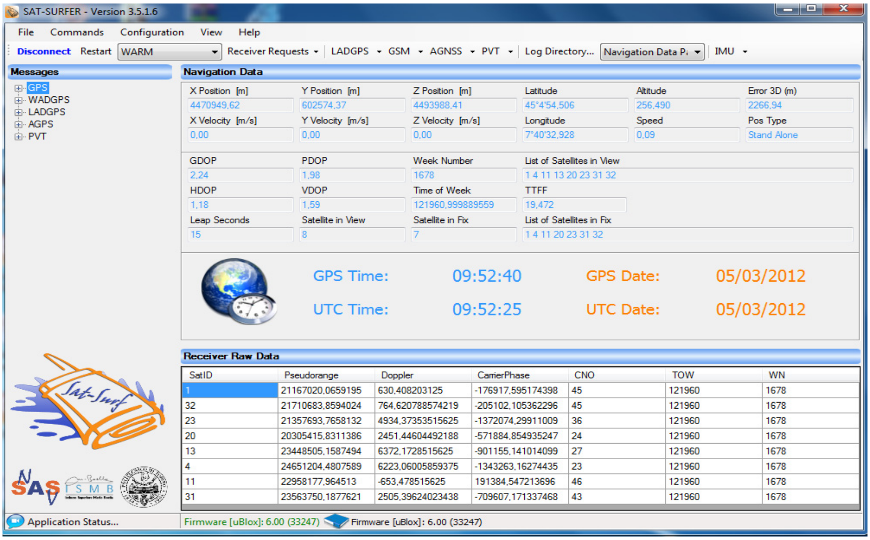
This work is divided in five major sections. In the first section we give a short introduction regarding the atmospheric errors. In the second section we describe in details the process of data collection and the tools used for measurements, then in the third section the implementation of our proposed PVT algorithm is presented. The fourth and fifth sections are dedicated to the obtained results, visualized with different kinds of plots. Finally we conclude our work with comments and conclusions.

2 Experimental Data Set

In this section we explain the GPS data collection process and the implementation of a post-processing adaptive PVT algorithm, where we included mathematical Ionospheric and Tropospheric correction models aiming to an improved accuracy of user's position estimation.

The single frequency measurements of the GPS pseudoranges were recorded using the SAT-SURF receiver, manufactured by ISMB [9]. Later on all the gathered data such as pseudoranges, Time Of Week, Week Number, the satellite's coordinates Xs, Ys and Zs, Ionosphere and Troposphere coefficients, were post-processed by the SAT-SURFER software. SAT-SURFER gets GPS raw data measurements, displays them on the screen and logs these data in different files allowing any further post-processing activity. Our real experiment and GPS data gathering was conducted outside our laboratory in the Lingotto Campus at nearly 1.30 PM. The GPS raw measurements displayed from SAT-SURFER in its GUI format are illustrated in Fig. 1.

The major error contribution in the overall user position accuracy comes from the Ionosphere layer, affecting mostly the vertical component and increasing in such way VDOP (Vertical Dilution of Precision) [10].The ionospheric parameters taken from the SAT-SURFER log files are ilustrated in Fig.2.



Navigation Data

X Position [m]: 4470949,62
Y Position [m]: 602574,37
Z Position [m]: 4493988,41
Latitude: 45°4'54,506
Altitude: 256,490
Error 3D (m): 2266,94
X Velocity [m/s]: 0,00
Y Velocity [m/s]: 0,00
Z Velocity [m/s]: 0,00
Longitude: 7°40'32,928
Speed: 0,09
Pos Type: Stand Alone
GDOP: 2,24
PDOP: 1,98
Week Number: 1678
List of Satellites in View: 1 4 11 13 20 23 31 32
HDOP: 1,18
VDOP: 1,59
Time of Week: 121960,999889559
TTFF: 19,472
Leap Seconds: 15
Satellite in View: 8
Satellite in Fix: 7
List of Satellites in Fix: 1 4 11 20 23 31 32

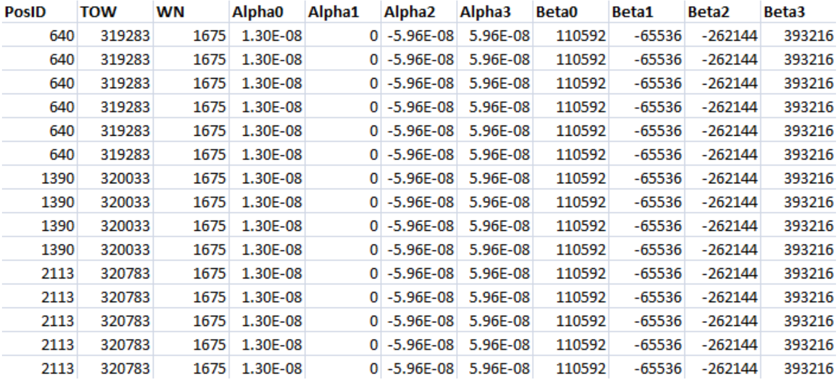
GPS Time: 09:52:40
GPS Date: 05/03/2012
UTC Time: 09:52:25
UTC Date: 05/03/2012

Receiver Raw Data

SatID	Pseudorange	Doppler	CarrierPhase	CNO	TOW	WN
1	21167020,0659195	630,408203125	-176917,595174398	45	121960	1678
32	21710683,8594024	764,620788574219	-205102,105362296	45	121960	1678
23	21357693,7658132	4934,37353515625	-1372074,29911009	36	121960	1678
20	20305415,8311386	2451,44604492188	-571884,854935247	24	121960	1678
13	23448505,1587494	6372,1728515625	-901155,141014099	27	121960	1678
4	24651204,4807589	6223,06005859375	-1343263,16274435	23	121960	1678
11	22958177,964513	-653,478515625	191384,547213696	46	121960	1678
31	23563750,1877621	2505,39624023438	-709607,171337468	43	121960	1678

Firmware [uBlox]: 6.00 (33247) Firmware [uBlox]: 6.00 (33247)

Fig. 1. SAT-SURFER Graphical User Interface (GUI)



PosID	TOW	WN	Alpha0	Alpha1	Alpha2	Alpha3	Beta0	Beta1	Beta2	Beta3
640	319283	1675	1.30E-08	0	-5.96E-08	5.96E-08	110592	-65536	-262144	393216
640	319283	1675	1.30E-08	0	-5.96E-08	5.96E-08	110592	-65536	-262144	393216
640	319283	1675	1.30E-08	0	-5.96E-08	5.96E-08	110592	-65536	-262144	393216
640	319283	1675	1.30E-08	0	-5.96E-08	5.96E-08	110592	-65536	-262144	393216
640	319283	1675	1.30E-08	0	-5.96E-08	5.96E-08	110592	-65536	-262144	393216
640	319283	1675	1.30E-08	0	-5.96E-08	5.96E-08	110592	-65536	-262144	393216
1390	320033	1675	1.30E-08	0	-5.96E-08	5.96E-08	110592	-65536	-262144	393216
1390	320033	1675	1.30E-08	0	-5.96E-08	5.96E-08	110592	-65536	-262144	393216
1390	320033	1675	1.30E-08	0	-5.96E-08	5.96E-08	110592	-65536	-262144	393216
1390	320033	1675	1.30E-08	0	-5.96E-08	5.96E-08	110592	-65536	-262144	393216
2113	320783	1675	1.30E-08	0	-5.96E-08	5.96E-08	110592	-65536	-262144	393216
2113	320783	1675	1.30E-08	0	-5.96E-08	5.96E-08	110592	-65536	-262144	393216
2113	320783	1675	1.30E-08	0	-5.96E-08	5.96E-08	110592	-65536	-262144	393216
2113	320783	1675	1.30E-08	0	-5.96E-08	5.96E-08	110592	-65536	-262144	393216
2113	320783	1675	1.30E-08	0	-5.96E-08	5.96E-08	110592	-65536	-262144	393216

Fig. 2. Ionospheric Correction parameters taken from SAT-SURFER log file

The α and β are the input data of our adaptive positioning algorithm necessary for the mitigation of ionospheric error in the user's position estimation. It will be later shown that we achieve a considerable improvement of the vertical component and a decreased VDOP, after the application of this correction in our main algorithm.

3 Implementation of Our Proposed Positioning Algorithm

In this section, we propose an innovative adaptive PVT algorithm compiled in MATLAB® environment. The specific computation flow diagram of our positioning algorithm is shown in Fig.3. This positioning algorithm is implemented as a recursive procedure with several iterations based on Least Square Mean (LSM) [11] solution and on Maximum Likehood (ML) criterion, minimizing in such way the search space for the " True User's position ". The initial step in our algorithm is the initialization of user position in Earth's Center in ECEF Coordinate System with coordinates LP = [0 0 0 0]. The linearization point will be updated after each Time Of Week (TOW) iteration, until the end of the iteration to become the evaluated user position. This algorithm is structured in two main iteration cycles: TOW and position loop. The two major goals of this algorithm are: 1) to provide the user position in a minimum number of iterations and 2) with the highest accuracy through the application of atmospheric correction models.

During the measurement phase, we were able to collect a considerable amount of GPS raw data from 2122 TOW and the mean number of fixed satellites were 6 (higher than the minimum requirement for a user position estimation).

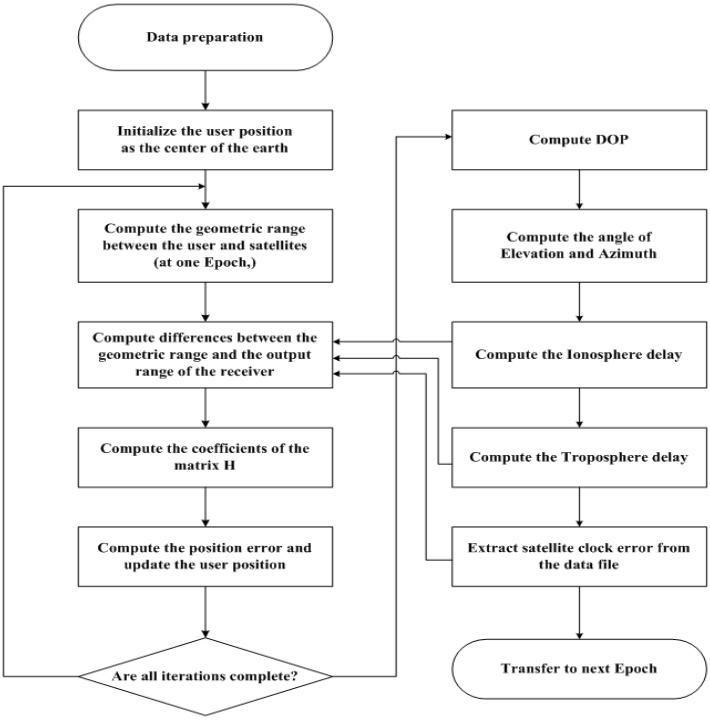


Fig. 3. Computational flow diagram of our Positioning algorithm

During the measurement phase, we were able to collect a considerable amount of GPS raw data from 2122 TOW and the mean number of fixed satellites were 6 (higher than the minimum requirement for a user position estimation).

4 Ionospheric and Tropospheric Correction Models

The focus of this section is to evaluate the ionospheric and tropospheric effect on GPS positioning solution. Prior to the correction models loop in our MATLAB® code, it is important to exclude from our computation the satellites with a C/N_0 lower than a predefined threshold. The threshold for C/N_0 was chosen to be equal to the mean value of the C/N_0 column in the data logs and was set to be C/N0 > 37 dBHz. This criterion is implemented in a Weighted Matrix and enables an increased accuracy in the user's position estimation.

```
Weight = Struct(TOW).Data(i).CNO;
W = diag(Weight(i));
```

The pseudoranges are affected by errors, which can be modeled as Gaussian random variables:

- With zero mean,
- Independent and identically distributed,
- with variance σ_{UERE}^2 .

The errors affecting the pseudoranges can be expressed by the following equation:

$$\rho = \ sqrt\ [(x_i - x_{Lp})^2 + (y_i - y_{Lp})^2 + (z_i - z_{Lp})^2] - \ c * t_{Lp} + c * T_a \quad (1)$$

where:

- $T_a = T_{Iono} + T_{Trop}$ – is the sum of Ionospheric and Tropospheric error contributions, respectively;
- $[x_i, y_i, z_i]$ – are the coordinates of user's unknown position;
- $[x_{Lp}, y_{Lp}, z_{Lp}]$ – are the coordinates of linearization point, which in our case is the position obtained from the last algorithm iteration;

We will describe in further details these two types of corrections that we take into account in the error affected pseudoranges.

4.1 Ionospheric Corrections

We propose the implementation of Ionospheric corrections based on the Klobuchar model [5].The Klobuchar model implemented in our algorithm uses as input:

- Receiver generated terms:

— λ_u - User Geodetic Latitude WGS 84 (semi – circles)
— ϕ_u - User Geodetic Longitude WGS 84 (semi – circles)

- E - Elevation angle between the user and the satellite , measure clockwise positive from the true north (semi- circles)
- A - Geodetic azimuth angle of the satellite
- *GPS time* - Receiver's computed system time.

- Satellite transmitted terms:

- α_n - coefficients of a cubic equation representing the amplitude of the delay.
- β_n - coefficients of a cubic equation representing the period PER of the model.

We designed a function *ionogen.m* to calculate the delay caused by Ionosphere layer, which was called in our main PVT algorithm. The main inputs of the ionospheric correction function are:

- *PER* is the period of the cosine function and implicates the interval of the ionospheric activity in daytime. It is expressed by the following formula, whose inputs are taken from the ionosphere log file:

$$PER = \beta_0 + \beta_1 * lat_m + \beta_2 * lat_m^2 + \beta_3 * lat_m^3 \tag{2}$$

where lat_m - is the geomagnetic latitude of the Earth's projection of the ionospheric intersection point (mean ionospheric height assumed to be 350 km).

- *Amplitude of the model*

$$AMP = \alpha_0 + \alpha_1 * lat_m + \alpha_2 * lat_m^2 + \alpha_3 * lat_m^3\ . \tag{3}$$

The inputs of the Klobuchar model were taken by loading the Elevation and Azimuth angles for each TOW and number of fixed satellites, using the following lines in MATLAB ®code:

```
azimuth   = Struct(TOW).Data(i).Azimuth;
elevation = Struct(TOW).Data(i).Elevation;
```

We observed that these coefficients are constant even for different TOW (Fig. 3) and this result is due to the fact that ionospheric parameters do not change in a short measurement time.

4.2 Tropospheric Corrections

As described in previous section, the signal refraction in the troposphere is separated into two components: the dry and the wet component, where the dry component contributes about 90 % of the total tropospheric delay. The tropospheric delay is approximated by using the Hopfield model [8], whose inputs in our algorithm are:

- *T temperature* in ^{0}C.
- *P pressure* in hPa.
- H_u *humidity ratio* in % .

- *R Earth radius:* R = 6371 km.
- *E Satellite Elevation angle.*

We designed a function in MATLAB® named *tropogen.m* to calculate the delay caused by the Troposphere layer, represented by the following relations:

- Total Tropospheric error contribution

$$\Delta\rho_{Tropospheric}(E) = \Delta\rho_{dry}(E) + \Delta\rho_{wet}(E) \tag{4}$$

where $\Delta\rho_{wet} = K_w(I(h_w) - b)$ and $\Delta\rho_{dry} = K_d(I(h_d) - b)$.

- Humidity ratio in % in dry and wet conditions is given by these equations:

$$H_w = 11000 \text{ and } H_d = 40136 + (148.72 * T) .$$

5 Plots and Results

In this section are presented the results of our work, which are visualized with different kinds of plots. In Figure 4 are plotted in Cartesian coordinates the true position of the user's receiver and the cloud of points which represent the estimated positions, outputs of our PVT algorithm for all GPS epochs.

We can easily observe that after applying the proposed ionospheric and tropospheric correction models, the error in the vertical component (height z) is significantly reduced.

Figure 5 shows the estimated positions and the true position in Geographical coordinates for a better understanding of the atmospheric residual errors. The Klobuchar model reduces the vertical error with a value equal to 33.7 m. The Tropospheric Hopfield model applied in our adaptive PVT algorithm, gives a slight correction to the vertical error in the amount of 1.5724 m. This was an expected outcome because Tropospheric error's impact is lower compared to the Ionospheric one, in the total error contribution. These important results are summarized in Table 1.

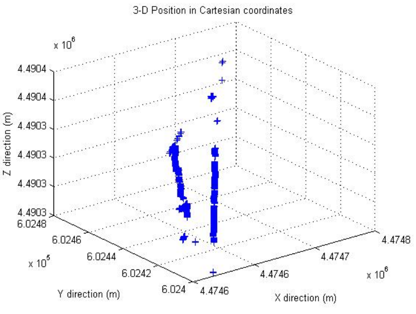


Fig. 4. 3-D estimated positions in Cartesian Coordinates

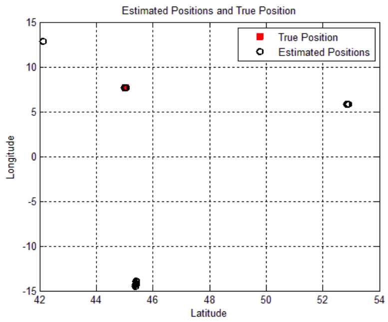


Fig. 5. Estimated positions and True position in Geographical coordinates

Table 1. Summary Table of the different trials computed for the PVT solution

	Latitude	**Longitude**	**Height (m)**
Without correction	45.0351^0	7.6704^0	45.1066
Ionosphere correction	45.0351^0	7.6704^0	11.4066
Troposphere correction	45.0351^0	7.6704^0	43.5342
Iono + Tropo correction	45.0351^0	7.6704^0	9.8342

Finally, the user's position estimated by our adaptive LMS algorithm for all GPS epochs or TOWs is:[45.0351^0 N 7.6704^0 E 9.8342 m], where we implemented a mathematical coordinates conversion function [XYZ to North East Height(m)].This estimated position is very close to the true position and this is illustrated in Fig. 6.

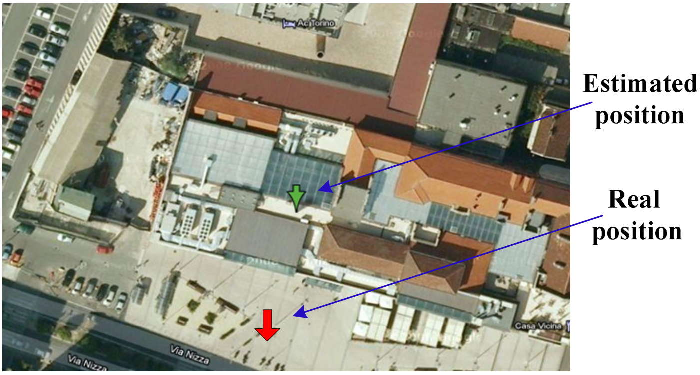


Fig. 6. Estimated user's position from our adaptive PVT algorithm in google map

6 Comments and Conclusions

At present, GPS system is the most widely available positioning tool. GPS signal propagating from the satellite to the users on ground is greatly affected by the atmospheric (Ionospheric and Tropospheric) effects, reducing in such way the position accuracy. The scope of this paper is the investigation of the performance impact of the atmospheric correction models in the overall positioning accuracy. We conducted real GPS raw measurements outside Lingotto campus with the scope of evaluating static user positioning, using SAT-SURF single frequency receiver manufactured by ISMB. We proposed an adaptive LMS algorithm, where we integrated Klobuchar and Hopfield mathematical correction models, enabling data post-processing. As it was expected, ionospheric effects were the largest source of error for high level accuracy of GPS positioning. With the application of Klobuchar model for Ionospheric correction, we achieved a reduction of the vertical error with a value equal to 33.7 m; however this model did not affect significantly the horizontal positioning. On the other hand, the integration of Hopfield Tropospheric model in our positioning algorithm, gave a slight improvement of the vertical error of 1.5724 m and mostly due to its dry component. An important factor enabling the fast and accurate convergence of the estimated positions to the true one, was the implementation of Weighted Matrix with the C/N_0 threshold set at 37 dB/Hz. This criteria enabled the discard of GPS pseudoranges that contributed to an increased positioning error. In this paper, we were concerned about the positioning performance of our algorithm for a static user and not taking into consideration the user's motion. However we are strongly confident that this issue can be overcome by restricting the C/N_0 threshold and increasing the number of iterations of the positioning algorithm.

In the future work, we will focus on the mitigation of other error's contribution such as relativistic, ephemerides and satellite clock errors. We will also investigate the positioning performance achieved after the application of EGNOS and differential corrections, using double frequency GPS receivers for PPP applications.

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