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Chapter

GPS Signal Multipath Error Mitigation Technique

Bharati Bidikar, Babji Prasad Chapa,
Mogadala Vinod Kumar and Gottapu Sasibhushana Rao

Abstract

The performance of GPS receiver depends on the accuracy of the range measurements. The predominant errors in range measurements are due to propagation path delays, making the measured range longer than it would be, if the signal has not reflected or refracted while propagating. In this chapter, an algorithm is proposed to mitigate the multipath error on the pseudorange measured from L1 carrier frequency. The error is estimated considering the linear combination of the GPS measurements and carrier frequencies of L band, viz. L1 and L2. This algorithm exploits the random nature of the multipath error and it avoids complex calculations involving sensitive parameter like reflection coefficient of the nearby reflectors. The multipath error is mitigated for standalone GPS receiver located in Indian subcontinent. Implementation of the algorithm shows pseudorange error due to multipath varied from 7 to 52 m, where the signals of low elevation satellites are most affected. GPS receiver position is calculated by considering multipath error corrected pseudoranges of all the visible satellites. This resulted in maximum error reduction of 30 m in receiver position estimates. This mitigation technique will be useful in selecting the site for GPS receiving antenna, where reflection coefficients are difficult to measure.

Keywords: GPS, L1 and L2 frequencies, elevation angle, pseudorange, carrier phase range, multipath error, ionospheric delay

1. Introduction

GPS finds its applications in most of the day to day activities of human life, viz. precise farming, surveying, missile guidance, military and civil aviation [1]. However, the accuracy, availability, reliability, and integrity of GPS navigation solution are impaired by various errors which are originating at the satellites, like orbital errors, satellite clock errors, etc. [2]; whereas, the receiver clock errors, multipath errors, receiver noise, and antenna phase center variations are the errors originating at the receiver [3]. Also, the propagation medium contributes to the delays in the GPS signal, as it passes through the ionosphere and troposphere [4]. In addition to these errors, the accuracy of the navigation solution is also affected by GPS satellites location as viewed by the receiver. Hence, error estimation and correction is a primary concern in precise navigation applications. In this chapter, the error originating at the receiver which is due to GPS signal multiple paths is addressed.

The signal transmitted by the satellite, taking multiple paths, affects both the pseudorange and carrier phase measurements [5]. But the effect of multipath on pseudorange is much higher than the carrier phase [6, 7]. The pseudorange multipath error in an urban environment is characterized by considering signal to noise ratio and elevation angle for DGPS [8]. The multipath effect on carrier phase measurements was also detected [9]. The GPS receiver cannot distinguish the direct signal from the several multipath signals. This problem in tracking loop was addressed by several authors [10, 11]. For the same GPS receiver, multipath error differs depending on the reflecting surfaces, viz. multipath effect due to large water bodies like sea surface. Multipath due to water bodies and its impact on the precision of GNSS positioning in marine application was also studied [12] and similar studied were done for static and kinematic receivers [13]. There are several studies mitigating the multipath error by antenna based mitigation methods. A choke ring antenna with ground plane to absorb multipath signals was proved to mitigate the error to large extent [14, 15]. Mitigation of the error and the performance of the receivers are analyzed for dual frequency receiver as well [16]. Some techniques also rely on the analysis of the signal-to-noise ratio values of GPS signals [17]. Apart from these methods the filter-based techniques are also implemented to extract or eliminate multipath effects, such as wavelet filters [18–20], Vondrak filter [21] and adaptive filter [22]. In precise positioning applications, multipath is a major error source and impact needs to be calculated especially in urban canyon while setting up GPS receiver antenna [23]. The multipath error originating at the receiver is very sensitive to geometry (like size and surface texture) and the reflection coefficients of the nearby reflectors [24]. These parameters limit the efficiency of the conventional multipath modeling methods. But in this chapter, an algorithm is proposed to calculate the multipath error affecting GPS L1 pseudorange range measurement. The algorithm utilizes the relationship between the code range measurements, carrier phase measurements and carrier frequencies (L1 = 1575.42 MHz and L2 = 1227.60 MHz) [25]. In this chapter, the multipath error affecting the pseudorange measurements of Satellite Vehicle Pseudorandom Noise (SVPRN) 07, 23, 28 and 31 are estimated using the proposed algorithm. The ephemerides data of these satellites for the entire day was collected on March 11, 2019, from a standalone GPS receiver, located in the Indian subcontinent. The proposed algorithm and the impact analysis done in this chapter will also be a valuable aid for setting up the GPS receiver antenna for air traffic control and navigation. Section 2 briefly explains the error budget and explains multipath error in detail. It also gives brief overview of the existing multipath error mitigation techniques. Section 3 gives the proposed multipath error estimation algorithm. Finally, the results and conclusions are given in Sections 4 and 5 respectively.

2. Multipath error in GPS

GPS measurements are biased by many errors. These errors are specific to each satellite signal and translate into a receiver position error (the receiver position being calculated from the estimated travel time of the signal from each satellite to the receiver). The errors are divided into three major groups as,

- Errors originating at the satellite like satellite clock error, ephemeris error, and error due to orbital eccentricity

- Errors originating in the propagation medium like ionospheric delay and neutral atmospheric delay
- Errors originating at the receiver like multipath error, receiver clock error, and instrument biases.

The major error sources their impact on PGS range measurements are given in **Table 1** [26].

A GPS signal may take several paths to a receiver's antenna and the signal can be reflected from buildings or ground and interfere with the direct signal creating a range error of several meters or more. The error impact on pseudorange measurement is much larger than that on the carrier phase. The inaccuracy in pseudorange directly affects the receiver position estimation. But for carrier phase measurements, the inaccuracy due to multipath will lead to a wide ambiguity search space and hence takes a longer time to resolve the ambiguity. This will result in incorrect determination of initial ambiguity which further leads to positioning errors. The signal delay due to multipath is very sensitive to the reflection coefficients of the nearby reflectors. These parameters limit the efficiency of the multipath modeling techniques. The impact of the multipath error on GPS satellite signal is given in the following sub section.

2.1 Multipath effect on GPS measurements

GPS receiver determines the pseudorange by code tracking and carrier tracking method. Code tracking method estimates the propagation time and carrier phase tracking method estimates phase delay between the received carrier and the locally generated signal. To measure the propagation time, i.e., the code range measurement, the locally generated code is shifted in time and correlated with the received signal. The correlation parameter is used by a discriminator to adjust the locally generated code with the received code and obtain the time delay. This time delay when scaled by the speed of light gives the range between the satellite and the receiver. A common code discriminator function used in GNSS receivers is the early correlator (E) minus Late correlator (L) values (E-L). The early correlator value is

Error source	Nominal values (m)	Remarks
Orbit	1–5	Error in broadcast ephemeris due to residual errors in curve fitting
Clock	3–5	Due to satellite clock drift
Ionosphere	2–50	Depends upon satellite elevation angle and solar activity
Troposphere	2–30	Depends upon the water vapor content in the lower part of atmosphere
Code multipath	15–150	Maximum 150 m using one chip correlator spacing and 15 m using 0.1 chip correlator spacing
Code noise	0.1–3	For C/A code. Depends upon receiver technology and dynamic stress
Carrier multipath	0.001–0.03	Maximum 4.75 cm for L1 carrier and 6.11 cm for L2 carrier
Carrier noise	0.0002–0.002	For L1 carrier. Depends upon receiver technology and dynamic stress

Table 1.
GPS error sources for SPS receivers.

the correlation between the incoming code and an early version of the locally generated code. The Late correlator value is the correlation value between the incoming code and a late version of the locally generated code. In the presence of multipath, the time delay is estimated by correlating the composite signal with locally generate code(s), which result in code measurement errors. The impact of multipath on code phase measurements can be up to half a chip equivalent to a range error of about 150 m for the GPS C/A code.

In a GPS receiver, the carrier phase is measured by accumulating the phase of the numerically controlled oscillator (NCO) output. In an environment, where there are no reflected signals, the incoming signal carrier is the same as the direct signal carrier. The NCO generated local carrier locks onto the direct carrier very accurately, and, as a result, the true phase difference between the incoming signal carrier and the locally generated carrier is nearly zero, (actually zero mean), at steady state. The resulting phase measurements are very accurate. In the presence of multipath, however, the composite signal phase shifts from the direct signal phase, and the NCO-generated local carrier locks onto the composite carrier phase, resulting in an error in the phase measurement. The processing of the received signal in GPS receiver is shown below.

The change in carrier phase due to multipath effect can be determined in the PLL section of the GPS receiver as shown in **Figure 1**. Following steps are carried out to extract the error in phase due to multipath,

Step 1: The direct signal received at the receiver is $Acos\varphi$. Here the "A" is amplitude and "φ" is phase angle.
Step 2: The reflected signal is modeled as $\alpha(Acos\varphi + \Delta\varphi)$, where "$\alpha$" is attenuation constant and "$\Delta\varphi$" is change in carrier phase of the maximum reflected signal.
Step 3: The composite signal received as the GPS receiver is

$$A \cos \varphi + \alpha(A \cos \varphi + \Delta\varphi) \tag{1}$$

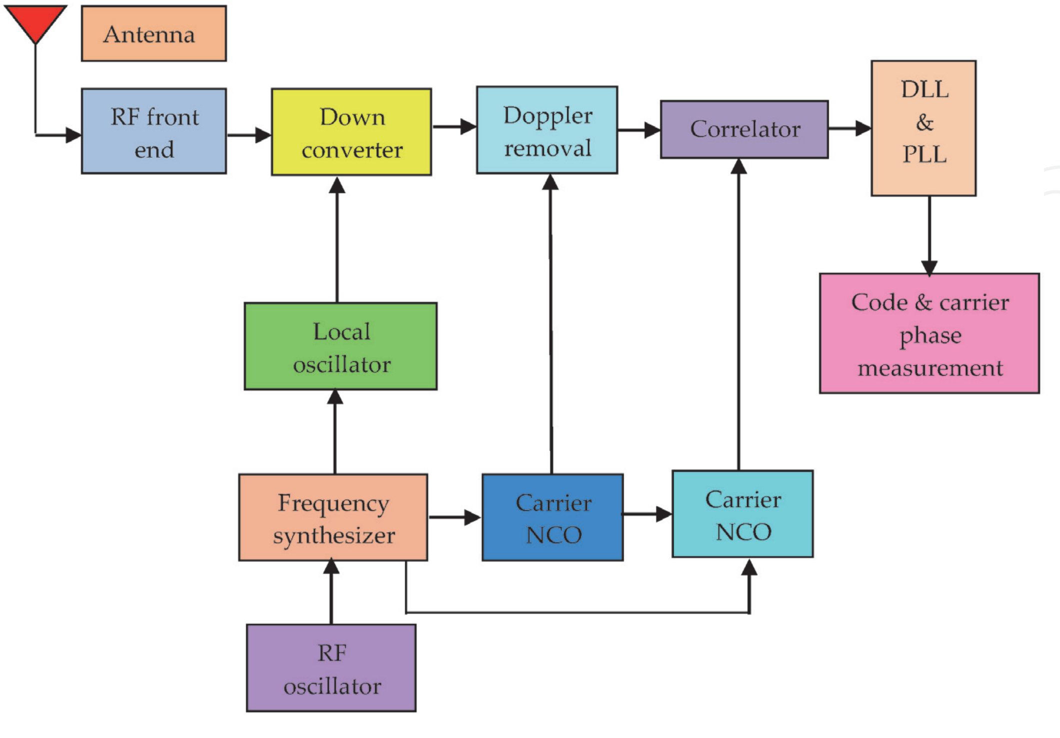

Figure 1.
GPS receiver block diagram showing extraction of code and carrier phase measurements from received composite signal.

Step 4: The error in phase measurement due to multipath is modeled as,

$$\delta\varphi = \tan^{-1}\left(\frac{\sin\ \Delta\varphi}{\alpha^{-1} + \cos\ \Delta\varphi}\right) \tag{2}$$

The above explained method involves tedious trigonometric relationship and is difficult to determine the error due to multipath. To mitigate the multipath error, highly sensitive GPS receivers utilize multiple narrow-spaced correlators. But most of the multipath mitigation techniques related to GPS receiver hardware are not cost effective and need complex hardware to implement; whereas the data processing methods to mitigate the multipath error are more effective. These methods involve correction of GPS code and carrier phase measurements. Multipath elimination delay lock loop are used to mitigate multipath at the receiver signal processing level [27]. Most modern GPS receivers now employ similar algorithms. However, multipath cannot be completely removed and the residuals may still be too large to ignore when high accuracy positioning results are required. The antenna based mitigation techniques involve the use of antenna with a high sensitivity to right-hand circular polarized (RHCP) signals, choke-ring-ground-plane antenna and antenna arrays. The reflected signals typically contain a large LHCP component. Multipath susceptibility of an antenna can be quantified with respect to the antenna's gain pattern characteristics by the multipath ratio (MRP) [28]. Most of the multipath error modeling or mitigation methods are complex to implement; hence in the following section, a multipath mitigation technique on pseudorange on L1 carrier is given, which makes the use of the linear combination of GPS measurements.

3. Pseudorange multipath error mitigation

Among the many errors affecting the GPS measurements [29], the predominant errors like ionospheric delay, multipath error and integer ambiguity are considered in the method. The range measurements on L1 and L2 carrier frequency are given by Eq. (3), (4), and (5).

$$P_{L1} = \rho + I_{L1} + MP_{L1} \tag{3}$$

where P_{L1} = pseudorange on L1 frequency [m]; ρ = geometric range [m]; I_{L1} = ionospheric delay on L1 frequency [m]; MP_{L1} = multipath error on P_{L1} [m].

$$\varphi_{L1} = \rho - I_{L1} + \lambda_{L1}N_{L1} + m\varphi_{L1} \tag{4}$$

$$\varphi_{L2} = \rho - I_{L2} + \lambda_{L2}N_{L2} + m\varphi_{L2} \tag{5}$$

where φ_{L1} = Carrier phase measurement on L1 frequency [m]; φ_{L2}= Carrier phase measurement on L2 frequency [m]; N_{L1}, N_{L2}= Integer ambiguity on L1 and L2 frequencies respectively; λ_{L1}=Wavelength of L1 carrier frequency [m]; λ_{L2}=Wavelength of L2 carrier frequency [m]; $m\varphi_{L1}$ = Multipath error on φ_{L1}[m]; $m\varphi_{L2}$= multipath error on φ_{L2} [m].

The multipath error in carrier phase measurements ($m\varphi_{L1}$ and $m\varphi_{L2}$) are assumed to be negligible compared to the error in pseudorange measurement. The expression for MP_{L1} can be obtained by forming the appropriate linear combination of code range and carrier phase measurements (subtract Eq. (4) from Eq. (3)).

$$\begin{aligned} P_{L1} - \varphi_{L1} &= 2I_{L1} - \lambda_{L1}N_{L1} + MP_{L1} \\ P_{L1} - \varphi_{L1} - 2I_{L1} &= MP_{L1} - \lambda_{L1}N_{L1} \end{aligned} \tag{6}$$

To make the above equation free from ionospheric delay, the Eq. (5) is subtracted from Eq. (4) and rearranged as below,

$$\varphi_{L1} - \varphi_{L2} = I_{L2} - I_{L1} + \lambda_{L1}N_{L1} - \lambda_{L2}N_{L2} \tag{7}$$

Since the ionosphere is dispersive medium, the delay is frequency dependent. Hence the delays (I_{L1} and I_{L2}) are related to the respective carrier frequencies (f_{L1} and f_{L2}) as,

$$(f_{L1}/f_{L2})^2 = I_{L2}/I_{L1} \tag{8}$$

By substituting the above equation for I_{L2} in terms of I_{L1}, we get

$$\begin{aligned} \varphi_{L1} - \varphi_{L2} &= (f_{L1}/f_{L2})^2 \times I_{L1} - I_{L1} + \lambda_{L1}N_{L1} - \lambda_{L2}N_{L2} \\ \varphi_{L1} - \varphi_{L2} &= \left((f_{L1}/f_{L2})^2 - 1\right) \times I_{L1} + \lambda_{L1}N_{L1} - \lambda_{L2}N_{L2} \end{aligned} \tag{9}$$

Simplifying Eq. (9) we get,

$$I_{L1} = 1/\left((f_{L1}/f_{L2})^2 - 1\right) \times (\varphi_{L1} - \varphi_{L2}) + 1/\left((f_{L1}/f_{L2})^2 - 1\right) \times (\lambda_{L2}N_{L2} - \lambda_{L1}N_{L1}) \tag{10}$$

Substituting the above expression for I_1 in Eq. (6) we get,

$$\begin{aligned} MP_{L1} - \lambda_{L1}N_{L1} = P_{L1} - \varphi_{L1} - 2/\left((f_{L1}/f_{L2})^2 - 1\right) \times (\varphi_{L1} - \varphi_{L2}) \\ + 2/\left((f_{L1}/f_{L2})^2 - 1\right) \times (\lambda_{L2}N_{L2} - \lambda_{L1}N_{L1}) \end{aligned} \tag{11}$$

Rearranging the terms in Eq. (11) we get,

$$\begin{aligned} MP_{L1} - \left(\lambda_{L1}N_{L1} - 2/\left((f_{L1}/f_{L2})^2 - 1\right) \times (\lambda_{L2}N_{L2} - \lambda_{L1}N_{L1})\right) \\ = P_{L1} - \left((f_{L1}/f_{L2})^2 + 1\right)/\left((f_{L1}/f_{L2})^2 - 1\right) \times \varphi_{L1} + 2/\left((f_{L1}/f_{L2})^2 - 1\right) \times \varphi_{L2} \end{aligned} \tag{12}$$

$$\begin{aligned} MP_{L1} = \left(\lambda_{L1}N_{L1} - 2/\left((f_{L1}/f_{L2})^2 - 1\right) \times (\lambda_{L2}N_{L2} - \lambda_{L1}N_{L1})\right)P_{L1} \\ - \left((f_{L1}/f_{L2})^2 + 1\right)/\left((f_{L1}/f_{L2})^2 - 1\right) \times \varphi_{L1} + 2/\left((f_{L1}/f_{L2})^2 - 1\right) \times \varphi_{L2} \end{aligned} \tag{13}$$

In above equation $\left(\lambda_{L1}N_{L1} - 2/\left((f_{L1}/f_{L2})^2 - 1\right) \times (\lambda_{L2}N_{L2} - \lambda_{L1}N_{L1})\right)$ is constant and expectation of MP_{L1} is assumed as zero. The impact of the multipath error and its variation with respect to elevation angle of the satellites for the entire duration of observation are analyzed. This analysis will be helpful in kinematic applications where multipath signal becomes more arbitrary, particularly in aircraft navigation and missile guidance where the reflecting geometry and the environment around the receiving antenna changes relatively in random way [29].

4. Results and discussion

Statistical analysis of the results shows that multipath error is too large to neglect. These errors are estimated for location having ECEF coordinates as x_u = 706970.90 m, y_u = 6035941.02 m, and z_u = 1930009.58 m in the Indian subcontinent for typical ephemerides data collected on March 11, 2019, from the dual frequency GPS receiver located at Department of Electronics and Communication Engineering, Andhra University College of Engineering, Visakhapatnam (Lat: 17.73°N/Long: 83.319°E), India. The city of Visakhapatnam with an area of 11,161 sq.kms is surrounded by Eastern Ghat Range, viz. Kailasa, Yarada and Narava hill ranges on north, south and west, respectively, and Bay of Bengal in the east. Due to this geography the GPS signals bound to get reflected. The data are collected on March 11, 2019, for entire 24 hrs with an epoch interval of 30 s. On March 11, 2019, the global geomagnetic activity index, i.e., Kp-index was 3. The average level for geomagnetic activity, i.e., Ap index was 2 and the noise level generated by the sun at a wavelength of 10.7 cm at the earth's orbit, i.e., solar index F10.7 was 69.5. These indices imply that on this particular day there was no solar storm or geomagnetic storm and the solar activity was normal. The solar activity affects the ionization in ionosphere and hence the signal propagation through this layer. The expression derived above for multipath error is ionospheric delay free. Hence the estimated multipath error is unaffected by ionospheric delay. For the observation period of 24 h, error analysis which is supported by the relevant graphs and tables are presented in this chapter. During this observation period, out of 32 satellites, minimum of 9 satellites were visible in each epoch. Though the error is computed and analyzed for all the visible satellites, the multipath error estimated for SV PRN07, 23, 28 and 31 are presented in this chapter. Navigation solution for each epoch is calculated using pseudoranges (multipath error corrected) of all the visible satellites.

Table 2 illustrates the multipath error for four satellites. Similar results were also obtained for all the visible satellites. Table also details the error in receiver position distance from the surveyed location. **Figure 2** shows the trajectories of the satellites 07, 23, 28 and 31 with respect to elevation and azimuth angles. The subplots of **Figure 3** show the change in multipath error with respect to change in elevation angle. **Figure 2** shows that the satellites were visible to the receiver at low elevation angle and rose to highest elevation angle of 70°, 84°, 52° and 82°, respectively. The receiver continued tracking the satellites. The satellites went out of the sight of the receiver when they set with low elevation angle. In each of the subplots **Figure 3** two curves of the change in multipath against the elevation angle are shown. One curve indicates the multipath error while the satellite was rising and the other when it was setting after reaching the highest elevation angle. From **Figure 3(a)–(d)**, it is

	Pseudorange multipath error on L1 frequency[m]				**Error in receiver position distance [m]**
	SV PRN07	***SV PRN23***	***SV PRN28***	***SV PRN31***	
Min	7.362	14.11	40.21	9.136	−25.8
Max	14.32	18.79	52.88	13.52	31.49
Standard deviation	1.816	1.439	1.984	1.019	10.78

Table 2.
Pseudorange multipath error for satellites signal on L1 frequency.

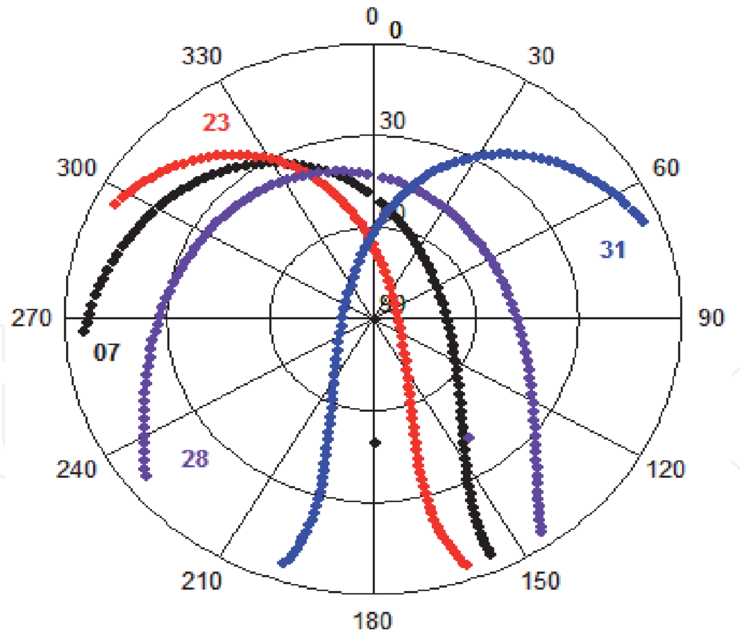

Figure 2.
Sky plot for the mentioned satellite orbits as viewed from GPS receiver located at Department of ECE, Andhra University (Lat: 17.73°N, Long: 83.31°E).

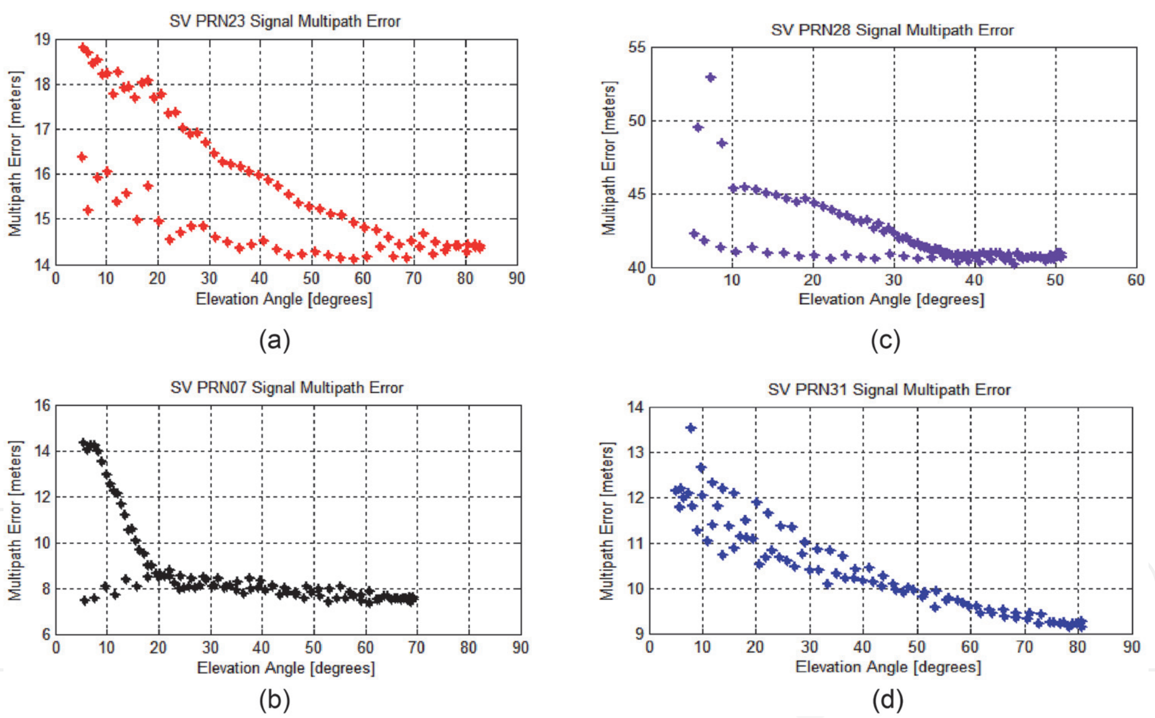

Figure 3.
(a)–(d) Pseudorange multipath error for respective satellites against the elevation angle for the observation period of 24 h.

observed that for the elevation angle of less than 10°, the multipath errors are 14.32 m, 18.79 m, 52.88 m and 13.52 m respectively. **Figure 4** shows the receiver position error in distance with respect to actual ECEF coordinates of the receiver. The figure shows the maximum error of 30 m. This is due to the residual errors in the pseudorange measurement. Though the pseudoranges of all the visible satellites are corrected for multipath error but the errors other than multipath remain uncorrected. The standard deviation of position error in distance is 10.78 m.

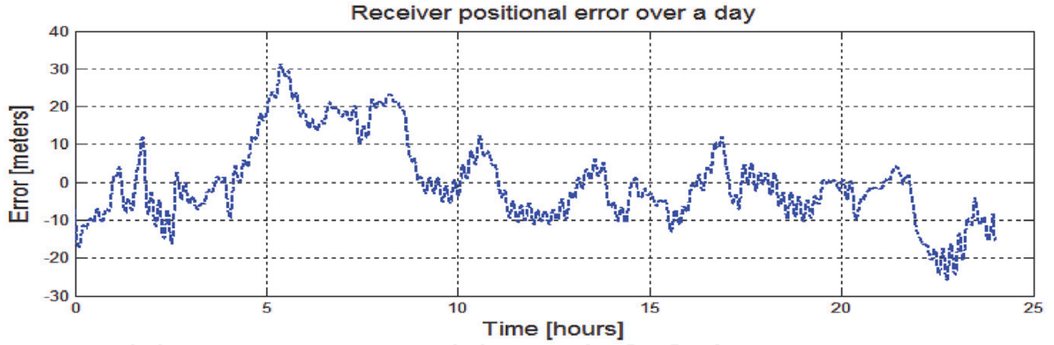

Figure 4.
Error in distance of GPS receiver position from surveyed position over the observation period of 24 h on March 11, 2019.

5. Conclusions

The statistics and result analysis comprises of investigation of error magnitude variations over a period of 24 h. Signals transmitted from the satellites, visible at low elevation angles, travel a longer path through the propagation medium and are subjected to multiple reflections than the satellites at higher elevation angle. From the results, the maximum multipath error of 52 m is observed for SVPRN28 at an elevation angle of 8° and minimum error of 7 m is observed for SVPRN7 at an elevation angle of 70°. But for SVPRN23, the minimum error is 14 m even though the elevation angle of the satellite is 84°. This is due to the multiple reflections the signal underwent for that particular azimuth angle, which determines the direction of the signal. The GPS receiver location is surrounded by high hill ranges and large water body, this would have led to multiple reflections and hence the large multipath error in spite of high elevation angle of the satellite. The receiver position error in distance with respect to actual position is 30 m. This is due to the residual errors in the pseudorange measurement as the errors other than multipath remain uncorrected. Along with the multipath error mitigation technique mentioned in this chapter, if other errors are also corrected the receiver position will be more accurate. The proposed algorithm to estimate multipath error is essential for all precise navigation applications (e.g., CAT I/II aircraft landings, missile navigation) and especially in surveying applications in urban canyon. The impact analysis done in this chapter will also be a valuable aid in selecting a location to set up the GPS receiver antenna with least multipath error for surveying, aircraft navigation and tracking.

Author details

Bharati Bidikar, Babji Prasad Chapa, Mogadala Vinod Kumar and Gottapu Sasibhushana Rao*
Department of Electronics and Communications Engineering, Andhra University College of Engineering (A), Andhra University, Visakhapatnam, India

*Address all correspondence to: sasigps@gmail.com

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