Progress In Electromagnetics Research M, Vol. 21, 133–148, 2011

ESTIMATION AND MITIGATION OF GPS MULTIPATH INTERFERENCE USING ADAPTIVE FILTERING

K. Yedukondalu[1, *], A. D. Sarma[2], and V. Satya Srinivas[2]

[1]Department of ECE, ACE Engineering College, Ankushapur, Ghatkesar Mandal, Ranga Reddy District, Andhra Pradesh-501 301, India

[2]Research and Training Unit for Navigational Electronics (NERTU), Osmania University, Hyderabad-500 007, India

Abstract—Estimation and mitigation of multipath error improves the positional accuracy of GPS. The objective of this paper is to estimate the effect of multipath interference at the receiver antenna based on both code and carrier phase measurements using Code minus Carrier (CMC) technique, and suggest a suitable method to mitigate it for static applications. Different adaptive filters such as Least Mean Squares (LMS) and various Recursive Least Squares (RLS) are considered to mitigate the error. The estimated multipath error for a typical signal is 0.8 m and 2.1 m on L_1 and L_2 carriers, respectively. The results due to adaptive filtering methods are encouraging and significant reduction of error (cm level) is observed. It is found that, when compared with experimental static dual frequency GPS receiver data, LMS and RLS filters give better error minimization on L_1 and L_2, respectively.

1. INTRODUCTION

Determination of satellite range and 3-D position using GPS depends on the quality reception and precise measurement of time delays of signals from all visible GPS satellites. The measurements are biased due to various error sources such as ionospheric error and receiver clock offsets. In addition to these, the range estimation faces problem of multipath leading to inaccurate estimation of user position. Multipath is a major source of error in many GPS applications which affects both pseudorange and carrier phase measurements. In multipath

Received 8 August 2011, Accepted 11 October 2011, Scheduled 14 October 2011
* Corresponding author: Kamatham Yedukondalu (kyedukondalu@gmail.com).

phenomenon, a signal arrives at an antenna through multiple paths due to signal reflections and/or diffraction. These reflections occur when the GPS satellite signal falls on different surfaces such as ground, reflectors etc before reaching the receiver. In such situations, GPS receivers based on single path assumption may estimate a wrong propagation time delay causing a positional error. The multipath is characterized by the amplitude, path delay, phase and phase rate of the reflected signal relative to the direct signal [1]. Multipath distorts the direct signal through interference with the reflected or indirect signals at the GPS antenna. Multipath errors should be dynamically modeled with respect to GPS receiver environment. Typically, carrier-phase multipath can reach a maximum value of a quarter of a cycle (about 4.8 cm for the L_1 carrier phase), and the pseudorange multipath can reach up to 293 m for the C/A-code measurements [2]. The fundamental analysis of GPS code and carrier multipath errors in GPS was reported by Hagerman [3].

Mitigation of multipath plays a prominent role in high precise navigation applications [4]. There are four prominent methods of multipath mitigation; all these methods have their own advantages and limitations.

i) The selection of low-multipath locations for antenna placement is an effective method. However, it is not possible to predict the level of multipath at a particular site prior to installation [5, 6].
ii) Hardware methods are antenna design, the use of microwave absorbing material, and receiver tracking, etc [7].
iii) Software methods include various algorithms developed to reduce unknown measurement error sources including multipath using Receiver Autonomous Integrity Monitoring (RAIM) schemes [8]. Various attempts have been made to estimate pseudorange multipath in kinematic applications using a Kalman filtering approach [9].
iv) By combining hardware and software (hybrid) methods to estimate multipath due to the spatial correlation of the measurements received from an array of antennas, but it requires the array to be static [10].

Even though most of the users can take advantage of above techniques, there is still multipath error in the measurements. Further improvements have to be done by data processing schemes. There are a wide variety of mitigation techniques which employ data processing schemes. Carrier smoothing takes advantage of the fact that carrier phase measurement errors typically are negligible compared to code multipath. Optimal combination of carrier and code phase measurements can efficiently reduce the code multipath to centimeter level and are widely used. Other typical methods are focusing on taking advantage of SNR measurements, repeatability of multipath at ground reference stations. Multiple receivers can be used for canceling spatial correlated multipath. A technique proposed by Linlin et al. (2000) to mitigate multipath using adaptive filter shows that forward filtering using data on two successive days is better than backward filtering [11]. Sleewaegen (1997) used Signal-to-noise ratio (SNR) information (data processing) to mitigate multipath error [12]. Xia (2001) and Satirapod et al. (2003) used wavelet algorithms to reduce multipath error [13, 14]. In this paper, multipath error estimation and mitigation is implemented based on data processing with software methods using the prominent adaption algorithms namely LMS and different types of RLS and comparative analysis is also made with the experimental results.

2. GPS MULTIPATH ERROR ESTIMATION

Direct and indirect signals received at the GPS receiver have relative phase offsets and the phase differences, which are proportional to the differences of the path lengths. Multipath error can be estimated by using a combination of code and carrier phase measurements. The pseudorange and phase measurements (in meters) on L_1 carrier frequency are modeled as [15]

$$\rho_{L_1} = R + c\left(\delta t_u - \delta t^s\right) + d_{orb} + I_{\rho L_1} + T + b + B + MP_{\rho L_1} + \varepsilon_{\rho L_1} \quad (1)$$

$$\phi_{L_1} = R + c(\delta t_u - \delta t^s) - \lambda_1 N_1 + d_{orb} - I_{\phi L_1} + T + b + B + MP_{\phi L_1} + \varepsilon_{\phi L_1} \quad (2)$$

where ρ_{L_1} is pseudorange, R is geometric (true) range, c is velocity of light, δt_u is user clock error, δt^s is satellite clock error, d_{orb} is orbital errors, $I_{\rho_{L_1}}$ is ionospheric error, T is tropospheric error, b is satellite hardware delay, B is receiver hardware delay, $MP_{\rho_{L_1}}$ is multipath error, and $\varepsilon_{\rho_{L_1}}$ is measurement noise on L_1 measurements in meters. $\lambda_1 N_1$ is integer ambiguity on L_1 and all the subscripts with ϕ are corresponding to the phase measurements. $MP_{\phi_{L_1}}$ and $\varepsilon_{\phi_{L_1}}$ are assumed to be small and negligible with carrier phase measurements. The troposphere, clock errors, orbital errors, satellite and receiver delays and relativistic effects are independent of frequency, which influence code and carrier phases by the same amount. In contrast to this, ionospheric refraction and multipath are frequency dependent [4]. By taking carrier phases and code ranges using a dual frequency GPS receiver and forming corresponding differences called Code minus carrier (CMC), all effects are cancelled except multipath and measurement noise. CMC is used to approximate the pseudorange multipath (ignoring very small contributions of carrier multipath and measurement noise). This technique can be used to identify better location for installing base station for Differential GPS or Local Area Augmentation System (LAAS) applications.

$$CMC = \rho_{L_1} - \phi_{L_1} + K_1 \cong 2I_{\rho L_1} + MP_{\rho L_1} + \varepsilon_{\rho L_1} \tag{3}$$

The multipath (including measurement noise) on L_1 carrier is given as [16]

$$MP_{\rho L_1} + \varepsilon_{\rho L_1} \cong \rho_{L_1} - \phi_{L_1} - 2I_{\rho L_1} + K_1 \tag{4}$$

The constant K_1 (λ_1 N_1) is due to the integer ambiguity.

Using dual frequency receiver, the ionospheric delay on L_1 can be estimated as [17]

$$I_{\rho L_1} = \frac{f_{L_2}^2}{f_{L_1}^2 - f_{L_2}^2} \cdot (\phi_{L_1} - \phi_{L_2}) \tag{5}$$

By substituting Eq. (5) in Eq. (4) and by further simplifying it (Eq. (4)) gives the code or pseudorange multipath on L_1 and measurement noise (MP_{L_1}), which can be detected and quantified using a single receiver and given as

$$MP_{L_1} = \rho_{L_1} - \frac{f_{L_1}^2 + f_{L_2}^2}{f_{L_1}^2 - f_{L_2}^2} \cdot (\phi_{L_1}) + \frac{2f_{L_2}^2}{f_{L_1}^2 - f_{L_2}^2} \cdot (\phi_{L_2}) + K_1 \tag{6}$$

Similarly, the code multipath on L_2 and measurement noise can be quantified as:

$$MP_{L_2} = \rho_{L_2} - \frac{2f_{L_1}^2}{f_{L_1}^2 - f_{L_2}^2} \cdot (\phi_{L_1}) + \frac{f_{L_1}^2 + f_{L_2}^2}{f_{L_1}^2 - f_{L_2}^2} \cdot (\phi_{L_2}) + K_2 \tag{7}$$

By substuting L_1 and L_2 carrier frequencies (f_{L_1} and f_{L_2}) in Eqs. (6) and (7), we get [16]:

$$MP_{L_1} \cong \rho_{L_1} - \frac{9529}{2329} \cdot (\phi_{L_1}) + \frac{7200}{2329} \cdot (\phi_{L_2}) + K_1 \tag{8}$$

$$MP_{L_2} \cong \rho_{L_2} - \frac{11858}{2329} \cdot (\phi_{L_1}) + \frac{9529}{2329} \cdot (\phi_{L_2}) + K_2 \tag{9}$$

Using Eqs. (8) and (9), the multipath error on L_1 and L_2 can be estimated for all the samples of dual frequency GPS data. K_1 and K_2 are functions of unknown integer ambiguities and measurement noise, which can be assumed constant if there is no cycle slip in the carrier phase data [11].

Various experiments are conducted at Research & Training Unit for Navigational Electronics (NERTU), Osmania University, Hyderabad, India, to analyze the effect of multipath for a static station.

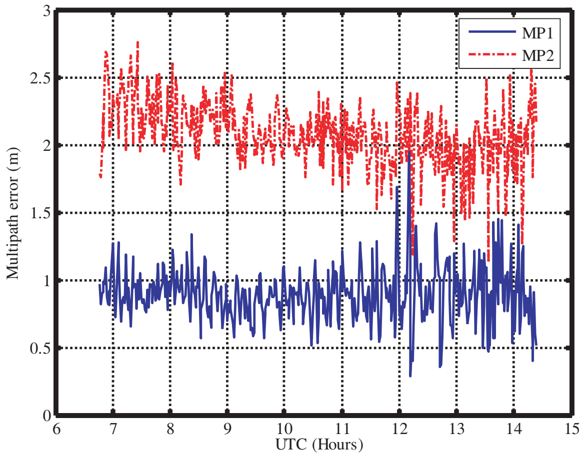

Figure 1. Multipath error on carrier frequencies L_1 (MP1) and L_2 (MP2).

For analysis, dual frequency GPS data was recorded on 8th August 2010 at 60sec. interval. The quantified multipath error for Satellite Vehicle 17 (SV 17) on L_1 (MP1) and L_2 (MP2) frequencies is shown in Figure 1. The mean multipath error on L_1 and L_2 are 0.8 m and 2.1 m respectively. L_1 signal consists of C/A code and P-Code with minimum received power of -160 dBW and -163 dBW respectively. But, L_2 signal consists of either C/A code or P-code (-166 dBW) only. Therefore, L_1 signal power is 3 dB more than L_2 [18]. Hence the error on L_2 is more than L_1. For analysis, data corresponding to this SV 17 is only presented through out this paper.

3. MITIGATION OF MULTIPATH ERROR USING ADAPTIVE ALGORITHMS

Adaptive algorithms have been applied to various problems including noise and echo cancellation, signal prediction, channel equalization, adaptive arrays etc. An adaptive filter can also be used to track the optimum behavior of slowly varying signals due to its real-time self-adjusting characteristic [19]. It consists of three basic processes:

1. Computing the output of filter in response to an input signal with a filtering process,
2. Generating an estimation error by comparing the output with a desired response,
3. Automatic adjustment of filter coefficients (adaptive process) in accordance with the estimation error.

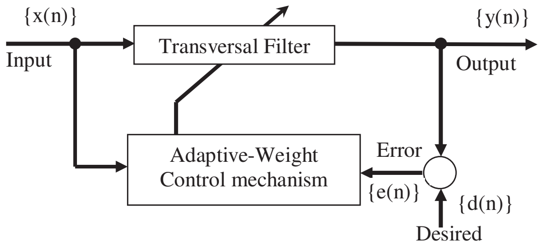

Figure 2. Typical block diagram of an adaptive transversal filter.

The combination of these three processes working together constitutes a feedback loop, as shown in Figure 2. A transversal filter is used for filtering process. The tap weights of this filter are adaptively controlled by an adaptive weight control mechanism. In this paper, a 32 stage adaptive transversal filter consisting of 31 delay elements is considered. Each delay element has its own weight coefficient with which the input sample is multiplied (output of this element). Based on the error signal, the adaptive weight control mechanism calculates the new coefficients, with which the transversal filter weights are multiplied (new weights for the transversal filter). Then the output response of the filter changes with respect to desired signal based on present weights of the filter. This process continues in feedback loop.

The pseudorange multipath errors as estimated by CMC technique using Eqs. (8) and (9) are applied to various adaptive filtering algorithms. A 32 stage FIR low pass filter with a highest cut off frequency of 0.5 Hz is designed to reduce medium and low frequency multipath [20]. The response of this filter is added to the multipath time series signal. The resulting signal is the desired signal, $\{d(n)\}$ for various filters. The input signal $\{x(n)\}$ of an adaptive filter is the multipath time series signal. Since the desired signal is generated by using $\{y(n)\}$ and $\{x(n)\}$, the desired signal $\{d(n)\}$ is uncorrelated with $\{x(n)\}$. The response of the RLS filter is $\{y(n)\}$ and error of the output is $\{e(n)\}$, which are given by [19]:

$$y(n) = \sum_{k=0}^{m-1} w_k x\left(n-k\right) \tag{10}$$

$$e(n) = d(n) - y(n) \tag{11}$$

$$\text{where } \xi(w_0, w_1, \ldots, w_{m-1}) = \sum_{n=n1}^{n2} |e(n)|^2 \tag{12}$$

As per the method of least squares, here the sum of error squares is chosen as minimum as possible. The weights of the filter

Table 1. Optimized parameters of various RLS filters.

S.No	Filter	Correlation matrix	Forgetting factor (λ)
1.	RLS	$0.1.[\mathrm{I}]_{32\mathrm{x}32}$	0.99
2.	HRLS	$\sqrt{10}.[\mathrm{I}]_{32\mathrm{x}32}$	0.99
3.	QRDRLS	$\sqrt{0.1}.[\mathrm{I}]_{32\mathrm{x}32}$	0.99
4.	HSWRLS	$\sqrt{10}.[\mathrm{I}]_{32\mathrm{x}32}$	0.99

$(w_0, w_1, \ldots, w_{m-1})$ are adjusted with feedback of error signal such that the error will converge to zero. The convergence time depends on how the initial correlation matrix is chosen and how the adaptive weights are calculated. Here, the performance of various adaptive algorithms for multipath error mitigation is compared. LMS filter and another four different RLS filters are designed by adjusting various parameters using Haykin (2007) [19, 21]. RLS filters considered here are: 1) Simple RLS (RLS), 2) House holder RLS (HRLS), 3) QR Decomposed RLS (QRDRLS) and 4) House holder Sliding Window RLS (HSWRLS) with block length of 64. The optimized parameters of these filters are listed in Table 1, such that the multipath reduction is considerably better [22].

4. EXPERIMENTAL RESULTS AND DISCUSSION

Several experiments are conducted to study the effect of multipath at the GPS receiver antenna site and to suggest a suitable and simplest technique to mitigate multipath effect for both static and real time applications. For the analysis, data corresponding to SV 17 is considered. Here, the performance of various adaptive filters to mitigate multipath error is compared. The multipath minimization efficiency of the adaptive filter is known by considering how much the input error signal is reduced at its output. Various filter outputs (minimized multipath error mean and standard deviations) are presented in Table 2 for comparison. The percentage of multipath error reduced by the filter outputs can be estimated as [(Yi)/Xi]*100, $i = 1, 2$. Here Xi and Yi are the mean multipath errors before and after filtering. From Figure 1, it is observed that X1 and X2 are 0.8 m and 2.1 m, respectively. Y1 and Y2 are given in Table 2.

The multipath error reduced by 92.52% for L_1 and 90.25% for L_2 by the LMS filter (Figures 3 and 4) is observed. This indicates the effectiveness of the filter. Hence, this simplest LMS filter can be applied to mitigate multipath error for static GPS applications. This type of filters can also be used for other receivers such as Coherent

Table 2. Comparison of various adaptive filter outputs.

S.No.	Filter type	Filter output (minimized multipath error)				% of Reduced Multipath error = [(Yi)/Xi]*100, i=1,2	
		MP1 (cm)		MP2 (cm)			
		Mean (Y1)	STD	Mean (Y2)	STD	MP1	MP2
1.	LMS	5.53	70.82	11.95	132.32	92.52	90.25
2.	RLS	12.02	123.4	19.23	158.92	72.39	83.42
3.	HRLS	12.46	125.26	19.59	160.55	68.30	81.84
4.	QRDRLS	12.46	125.26	19.59	160.55	68.30	81.84
5.	HSWRLS	12.47	125.21	19.61	161.10	68.50	81.92

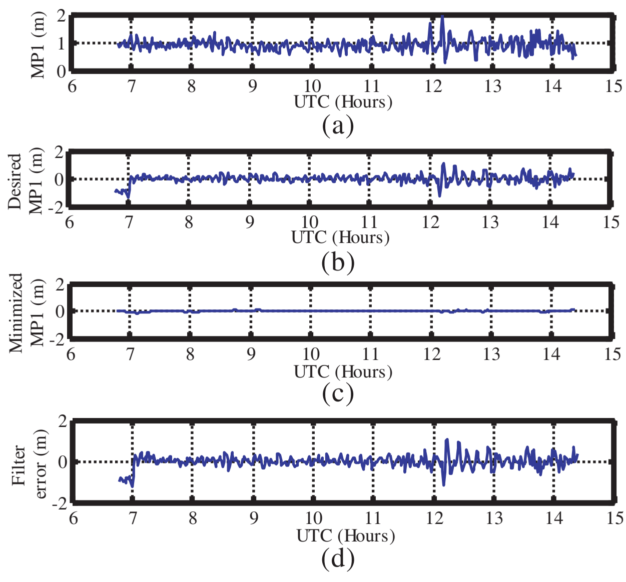

Figure 3. Multipath mitigation using LMS adaptive filter on L_1 of SV17 (14 Aug. 2010). (a) Multipath error (MP1). (b) Desired MP1. (c) Minimized MP1. (d) Filter convergence error.

Radio Beacon Experiment (CRABEX) [23].

The error is reduced by 72.39% and 83.42% with convergence time of 2.68 hrs and 2.73 hrs for MP1 and MP2, respectively, by the simple RLS adaptive filter (Figures 5 and 6). The multipath error is reduced by 68.30% and 81.84% for MP1 and MP2 (Figures 7 and 8) by HRLS. But, this filter is taking less time (0.68 and 0.38 hrs for MP1 and MP2

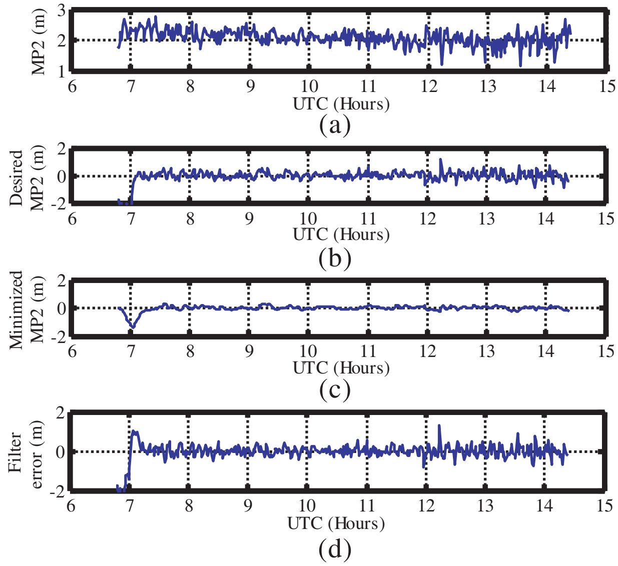

Figure 4. Multipath mitigation using LMS adaptive filter on L_2 of SV17 (14 Aug. 2010). (a) Multipath error (MP2). (b) Desired MP2. (c) Minimized MP2. (d) Filter convergence error.

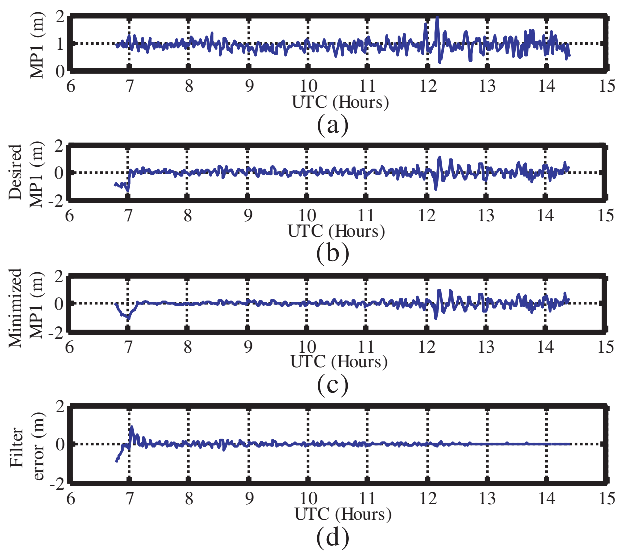

Figure 5. Multipath mitigation using RLS adaptive filter on L_1 of SV17 (14 Aug. 2010). (a) Multipath error (MP1). (b) Desired MP1. (c) Minimized MP1. (d) Filter convergence error.

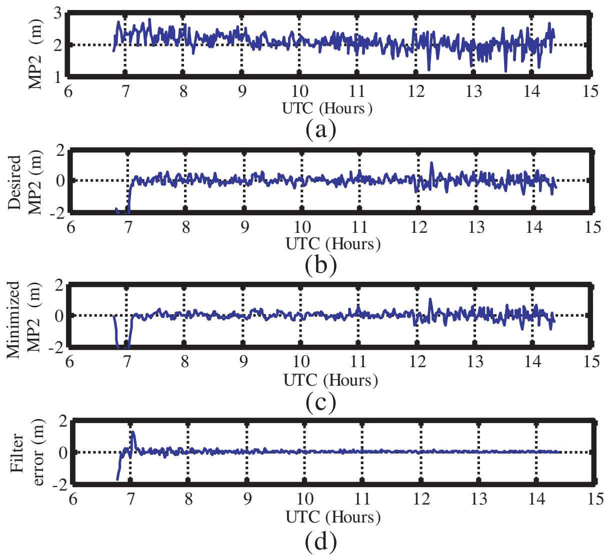

Figure 6. Multipath mitigation using RLS adaptive filter on L_2 of SV17 (14 Aug. 2010). (a) Multipath error (MP2). (b) Desired MP2. (c) Minimized MP2. (d) Filter convergence error.

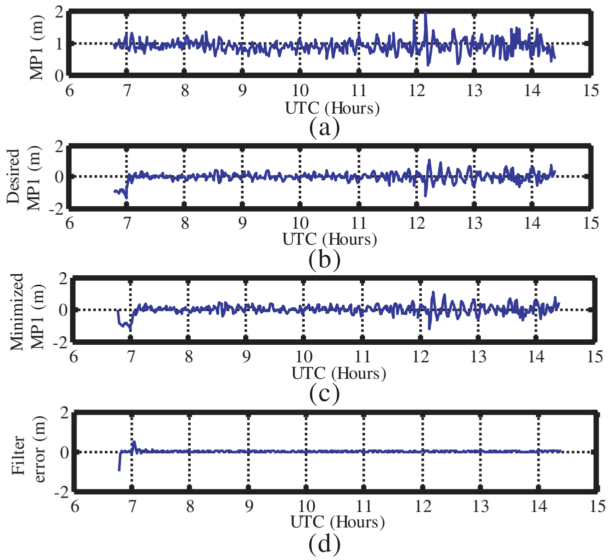

Figure 7. Multipath mitigation using HRLS adaptive filter on L_1 of SV17 (14 Aug. 2010). (a) Multipath error (MP1). (b) Desired MP1. (c) Minimized MP1. (d) Filter convergence error.

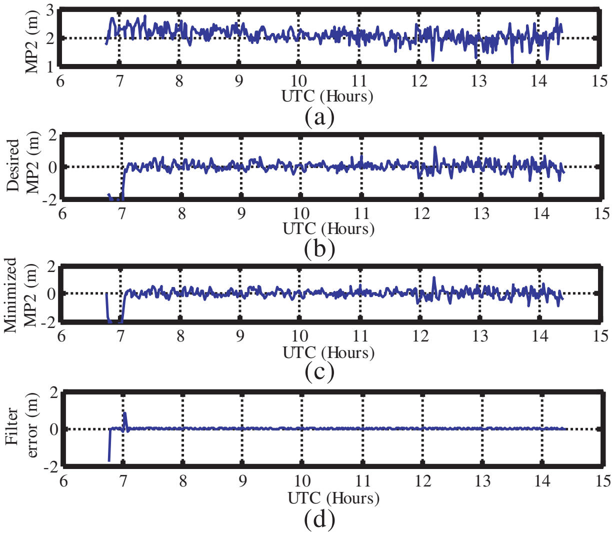

Figure 8. Multipath mitigation using HRLS adaptive filter on L_2 of SV17 (14 Aug. 2010). (a) Multipath error (MP2). (b) Desired MP2. (c) Minimized MP2. (d) Filter convergence error.

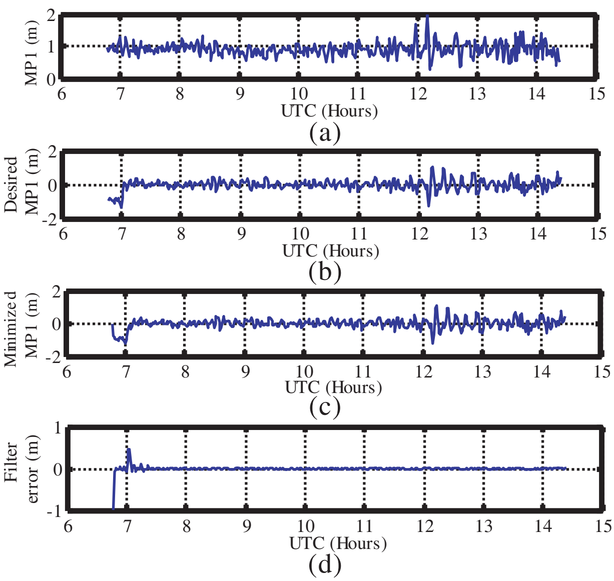

Figure 9. Multipath mitigation using QRDRLS adaptive filter on L_1 of SV17 (14 Aug. 2010). (a) Multipath error (MP1). (b) Desired MP1. (c) Minimized MP1. (d) Filter convergence error.

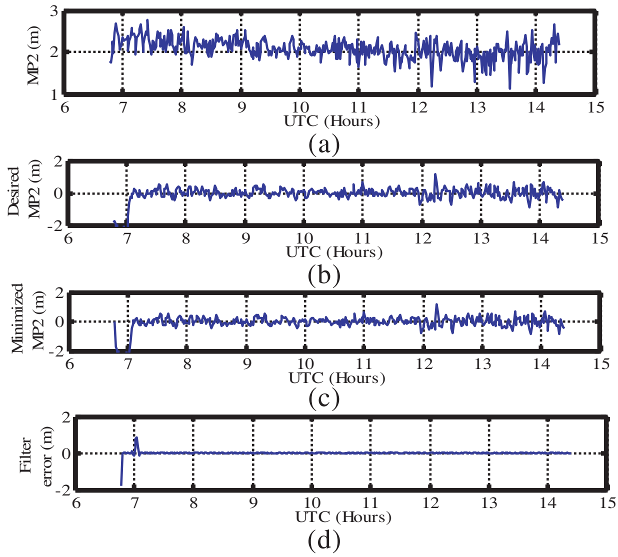

Figure 10. Multipath mitigation using QRDRLS adaptive filter on L_2 of SV17 (14 Aug.2010). (a) Multipath error (MP2). (b) Desired MP2. (c) Minimized MP2. (d) Filter convergence error.

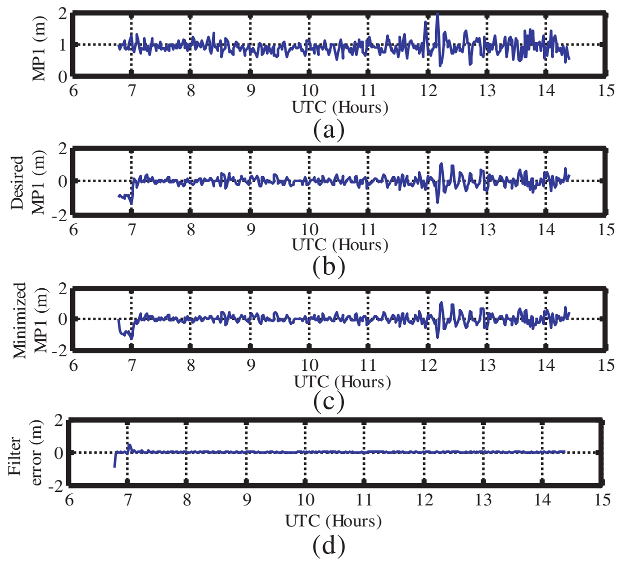

Figure 11. Multipath mitigation using HSWRLS adaptive filter on L_1 of SV17 (14 Aug. 2010). (a) Multipath error (MP1). (b) Desired MP1. (c) Minimized MP1. (d) Filter convergence error.

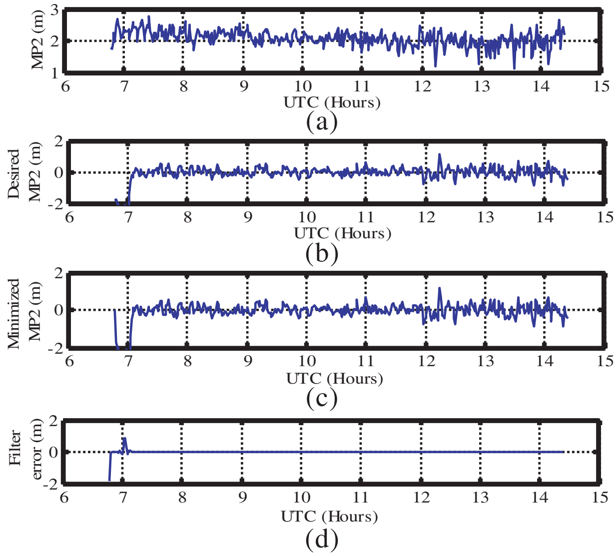

Figure 12. Multipath mitigation using HSWRLS adaptive filter on L_2 of SV17 (14 Aug. 2010). (a) Multipath error (MP2). (b) Desired MP2. (c) Minimized MP2. (d) Filter convergence error.

respectively) for the filter error to converge at zero. The performance of QR decomposed RLS filter is similar to that of HRLS filter (Figures 9 and 10) with respect to both convergence time and efficiency. With House holder Sliding Window RLS filter, error is reduced by 68.5% and 81.9% with convergence time of 0.69 hrs and 0.39 hrs for MP1 and MP2 (Figures 11 and 12) respectively.

It is observed that LMS filter efficiency is more than various RLS filters. LMS filter takes larger convergence time. And also the error minimized is more on L_1 than on L_2 by the LMS filter, which is reversed for various RLS filters. Therefore, LMS filter is suitable for static navigation and/or single frequency (L_1) applications. But, the RLS filters can be used for minimizing error on L_2 for more precise navigation applications with dual or more frequency receivers. It is observed that the MP2 is noisier than MP1 (Figure 1). L_1 signal is less contaminated by noise than L_2, due to the fact that L_1 signal strength is stronger than L_2. But, the convergence of RLS filters is faster than the conventional LMS filters. That is, RLS filters can be used for real-time kinematic navigation applications due to the fact that multipath is more pronounced for kinematic applications. The convergence speed of the adaptive filter depends on the step size and length of the filter. The convergence speed is estimated from the Mean

Square Error (MSE) of error signal $\{e(n)\}$, is given by [19]:

$$MSE = \frac{\sum\limits_{k-1}^{N} e_k^2\,(n)}{N} \tag{13}$$

where N is the number of samples, and $e_k(n)$ is the error at the kth sample of data. The convergence speed of the filter can be increased by considering more data samples in a given time. Therefore, GPS data should be recorded at higher sampling rates to increase the convergence speed.

5. CONCLUSIONS

In this paper, the multipath error estimation using CMC method is described, and estimated error with experimental data is presented. LMS and four different RLS adaptive filtering algorithms are used to mitigate the multipath error. The results are encouraging, and the multipath error is reduced by $\sim 90\%$ and $\sim 72\%$ with LMS and RLS filters, respectively. A significant feature of the LMS algorithm is its simplicity. Therefore, the LMS filter can be applied to mitigate multipath error on L_1 for static GPS applications such as installing base station for DGPS and Local Area Augmentation System (LAAS) applications [20]. For high precision navigation applications, GPS receiver is required to process both L_1 and L_2 signals. RLS filter can be used to mitigate multipath error for both L_1 and L_2 carrier frequencies [22]. Both of the LMS and RLS filters can be used in multi-constellation wide band Global Navigation Satellite Systems (GNSS) receivers. Wide band receivers are very prone to noise; hence more care should be taken while designing the multi-constellation antennas [24].

ACKNOWLEDGMENT

The above work has been carried out under the project entitled "Investigation of atmospheric effects on future ground based augmentation for GPS systems", sponsored by Department of Science and Technology (DST), New Delhi. Vide sanction letter No: SR/S4/AS: 53/2010, Dated: 12th July, 2010.

REFERENCES

1. Braasch, M. S., "Multipath effects," *Global Positioning System: Theory and Applications*, B. W. Parkinson and J. J. Spilker (eds.), Vol. 1, AIAA, 1996.

2. El-Rabbany, A., *Global Positioning System*, Artech House Publishers, 2002.
3. Hagerman, L., "Effects of multipath on coherent and non coherent PRN ranging receiver," *Aerospace Rep. TOR-0073 (3020-03)-3*, Development Planning Division, the Aerospace Corporation, May 15, 1973.
4. Hofmann-Wellenhof, B., H. Lichtenegger, and J. Collins, *Global Navigation Satellite Systems*, 5th revised edition, Springer-Verlag, Berlin Heidelberg, New York, 2007.
5. Bilich, A. and K. M. Larson, "Mapping the GPS multipath environment using the signal-to-noise ratio (SNR)," *Radio Sci.*, Vol. 42, RS6003, 2007, doi: 10.1029/2007RS003652.
6. Christopher, J. C. and A. Penina, "Adaptive SNR-based carrier phase multipath mitigation technique," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 34, No. 1, 264–276, January 1998.
7. Ray, J. K., M. E. Cannon, and P. Fenton, "Code range and carrier phase multipath mitigation using SNR, range and phase measurements in a multi-antenna system," *Proceedings of the 12th International Technical Meeting of the Satellite Division of The Institute of Navigation*, 1025–1034, September 14–17, 1999.
8. Parkinson, B. W. and P. Axelrad, "Autonomous GPS integrity monitoring using the pseudorange residual," *Journal of the Institute of Navigation*, Vol. 35, No. 2, 255–274, 1988.
9. De Jong, K., "The Influence of code multipath on the estimated parameters of the geometry-free GPS model," *GPS Solutions*, Vol. 3, No. 2, 11–18, 1999.
10. Jonathan, H. W., R. J. Davis, and E. N. Rosario, "Multipath mitigation performance of planar GPS adaptive antenna arrays for precision landing ground stations," *13th International Technical Meeting of The Satellite Division of The Institute of Navigation*, 1–8, Salt Lake City, Utah, September 2000.
11. LinLin, G. E., S. Han, and C. Rizos, "Multipath mitigation of continuous GPS measurements using an adaptive filter," *GPS Solutions*, Vol. 4, No. 2, 19–30, 2000.
12. Sleewaegen, J., "Multipath mitigation, benefits from using the signal to noise ratio," *Proceedings of ION GPS-97*, 531–540, Kansas City, September 16–19, 1997.
13. Xia, L., "Approach for multipath reduction using wavelet algorithm," *Proceedings of International Technical Meeting of the Satellite Division of the Institute of Navigation*, 2134–2143,

Kansas City, September 11–14, 2001.

14. Satirapod, C., R. Khoonphool, and C. Rizos, "Multipath mitigation of permanent GPS stations using wavelets," *International Symposium on GPS/GNSS*, Tokyo, 2003.
15. Hatch, R., "The synergism of GPS code and carrier measurements," *Proceedings of the 3rd International Geodetic Symposium on Satellite Doppler Positioning*, 1213–1231, February 1982.
16. Rizos, C., "Principles and practice of GPS surveying," Monograph 17, 555, School of Geomatic Engineering, The University of New South Wales, Sydney, Australia, 1996.
17. Misra, P. and P. Enge, *Global Positioning System: Signals, Measurements and Performance*, 2nd edition, Ganga Jamuna Press, 2006.
18. Kaplan, D., *Understanding GPS: Principles and Applications*, Artech House, Booston, London, 1996.
19. Haykin, S., *Adaptive Filter Theory*, 4th edition, Pearson Education Inc., 2007.
20. Yedukondalu, K., A. D. Sarma, and V. Satya Srinivas, "Multipath mitigation using LMS adaptive filtering for GPS applications," *Applied Electromagnetics Conference (AEMC-2009)*, Kolkata, India, December 14–16, 2009.
21. Liu, H., X. Li, L. Ge, C. Rizos, and F. Wang, "Variable length LMS adaptive filter for carrier phase multipath Mitigation," *GPS Solutions*, Vol. 15, 29–38, 2011, doi 10.1007/s10291-010-0165-9.
22. Yedukondalu, K., A. D. Sarma, and A. Kumar, "GPS multipath interference mitigation using recursive least squares adaptive filtering," *2010 IEEE Asia Pacific Conference on Circuits and Systems*, 104–107, Kuala Lumpur, Malaysia, December 6–9, 2010.
23. Rama Krishna Rao, B., Y. Ravi Kumar, D. Venkata Ratnam, D. Krishna Reddy, and A. D. Sarma, "Investigation of EMI and multipath effects on CRABEX receiver," *EMC Journal*, Chennai, India, October 2006.
24. Kumar, A., A. D. Sarma, A. K. Mondal, and K. Yedukondalu, "A wide band antenna for multi-constellation GNSS and augmentation systems," *Progress In Electromagnetic Research M*, Vol. 11, 65–77, 2010.