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Mitigating Multipath Errors in NavIC Receivers for Marine Environments: An Adaptive Filtering Approach

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Abstract

The Navigation with Indian Constellation(NavIC) is Regional Based Satellite Navigation System, is developed and operated by the Indian Space Research Organization(ISRO). It provides accurate real-time positioning and timing services encompassing India's mainland and 1500km radius around it. Its operational frequencies (L5 at 1176.46MHz, S1 at 2492.028MHz) can pose distinctive challenges, especially in maritime environment. To study multipath errors induced by sea surface, an experiment was carried out at Kakinada sea shore, Kakinada, Andhra Pradesh. Accord make receiver is kept on one side of the boat, sailed from Kakinada sea coast (16^o 59'1.94''N,82^{o}17'3.87''E) to Hope Island(16^{o}58'57.87''N,82^{o}19'39.88''E).The analysis is done using Code Minus Carrier (CMC) method for estimating multipath errors affected due to sea surface and applied adaptive filtering techniques like Recursive Least Squares (RLS), Least Mean Squares (LMS), and Normalized Least Mean Squares (NLMS) filters to mitigate the multipath error, Multipath error is estimated as maximum 1.98m on L5 and 2.32m on S1 frequencies. LMS, NLMS filter techniques reduced the multipath error by 98% on L5 and 99% on S1 frequencies.

1. Introduction

Navigation with Indian Constellation (NavIC) is a regional satellite navigation system to provide precise positioning, navigation, and timing (PNT) applications within a limited service region. The system is fully operational and consists of three Geostationary Orbital (GEO) satellites and four Geosynchronous Orbital (GSO) satellites. NavIC offers two service classifications: The Standard Positioning Service (SPS) for civilian users and the Restricted Service (RS) for authorized users. Both services utilize distinctively modulated L5 and S signals. Civilian users receive Binary Phase-Shift Keying (BPSK) modulation under the SPS, whereas authorized users are provided with Binary Offset Carrier (BOC) modulation under the RS. Numerous research endeavors have delved into assessing the accuracy of positioning with IRNSS. The utilization of Global Navigation Satellite Systems (GNSS) has grown, resulting in heightened requirements for precise positioning.

Diverse sources of error, such as satellite clock inaccuracies, ionospheric and tropospheric delays, orbital deviations, and multipath disturbances, impact the precision of GNSS positioning. Despite the potential of differential positioning and model adjustments to reduce errors stemming from satellite clock, ionospheric and tropospheric delays, and orbital deviations, Multipath interference remains a persistent hurdle [1]. Given the absence of a comprehensive solution to eliminate multipath interference, effective strategies for minimizing and alleviating multipath error is essential, particularly for applications necessitating high levels of precision [2,3].

Upon transmission of an electromagnetic wave signal by a satellite, a portion of it directly travels to the ground receiver, while another part may indirectly reach the receiver through reflection or refraction caused by the surrounding medium and obstacles. The occurrence in which the ground receiver captures both the direct and reflected/refracted signals is identified as multipath phenomenon [4]. In intricate settings like urban regions with tall structures, GNSS receivers are more vulnerable to receiving multipath signals. Mitigating multipath error entails two major approaches: hardware improvements and data processing techniques. Hardware enhancements concentrate on antenna design and receiver enhancement, such as antenna designs such dual-polarization antennas and patch elements on choke rings are used. Receiver upgrades, such as the "narrow correlator" delay-locked loop and multipath estimating delay-locked loop, help to reduce multipath errors. Multipath errors may only be partially eliminated by these hardware advancements, which can be expensive. Multipath error mitigation can also be achieved through data processing techniques, such as wavelet analysis, adaptive finite impulse response filtering, and empirical mode decomposition[5].

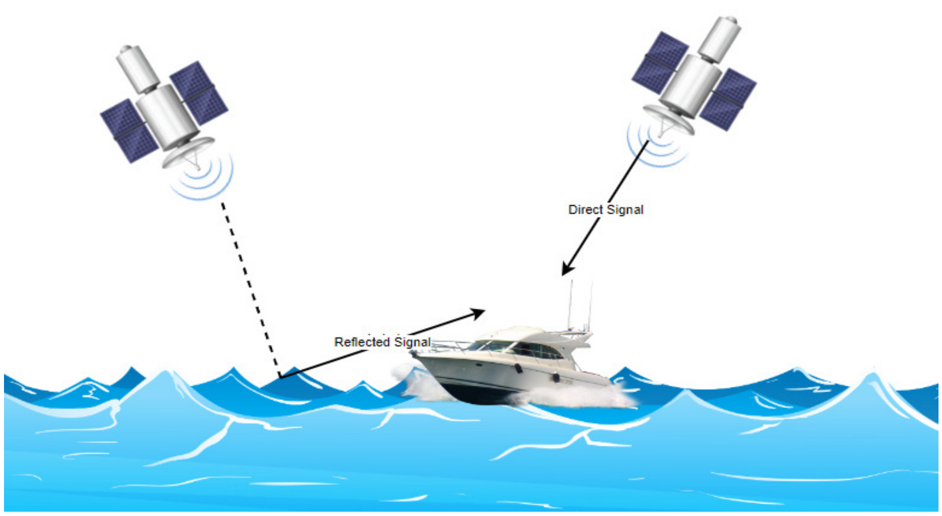

Figure 1. Multipath scenario in marine environment

2. Methodology

2.1 Code minus Carrier Technique:

Signals received by NavIC receivers, whether direct or indirect, exhibit relative phase discrepancies and variations in phase between code and carrier phase measurements. Consequently, utilization of code and carrier phase measurements becomes essential for assessing multipath effects on L5 and S1 through the employment of the CMC technique. The multipath evaluation on L5 and S1 can be defined as[6]:

$$MP_{L5}=\rho_{L5} - \frac{f_{l5}^2+f_{S1}^2}{f_{L5}^2-f_{S1}^2}.(\emptyset_{L1})+\frac{2f_{S1}^2}{f_{l5}^2-f_{S1}^2}.(\emptyset_{L2})+K_1 \quad (1)$$

$$MP_{S1}=\rho_{S1} - \frac{2f_{L5}^2}{f_{L5}^2-f_{S1}^2}.(\emptyset_{L2})+\frac{f_{L5}^2+f_{l2}^2}{f_{L5}^2-f_{S1}^2}.(\emptyset_{L2})+K_2 \quad (2)$$

Where ρ_{l5} is pseudo range of L5, ρ_{S1} is pseudo range on S1, and corresponds to code phase measurements on L5 and S1 carrier frequencies respectively, K1 and K2 depict functions of integer ambiguities and measurement noise, can be considered as a constant, considering no cycle slip in carrier phase.

$$MP_{L5}=\rho_{l5} - \frac{9529}{2329}.(\emptyset_{L5})+\frac{7200}{2329}.(\emptyset_{S1})+K_1 \quad (3)$$

$$MP_{S1}=\rho_{S1} - \frac{11858}{2329}.(\emptyset_{S1})+\frac{9529}{2329}.(\emptyset_{S1})+K_2 \quad (4)$$

Where MP_{L5} and $MP_{S1}$are code multipath on L5 and S1 respectively.

This methodology is extensively applied for multipath estimation and the selection of optimal NavIC receiver deployment locations. Adaptive filters are employed to alleviate multipath errors based on the code multipath evaluations derived from Equations (3) and (4).

2.2 Adaptive Filtering techniques

Adaptive filter methodologies are frequently employed for tasks such as noise mitigation, reverberation annulment, and interference mitigation in signal processing. A schematic representation in Figure 2 illustrates the architectural layout of an adaptive filter employing a lateral filter. The filter executes the filtration procedure, while the coefficients of the filter taps are supervised by an adaptive weight regulation mechanism[7]. A self-regulating adaptive filter executes the subsequent functions to monitor the optimal response of gradually changing signals

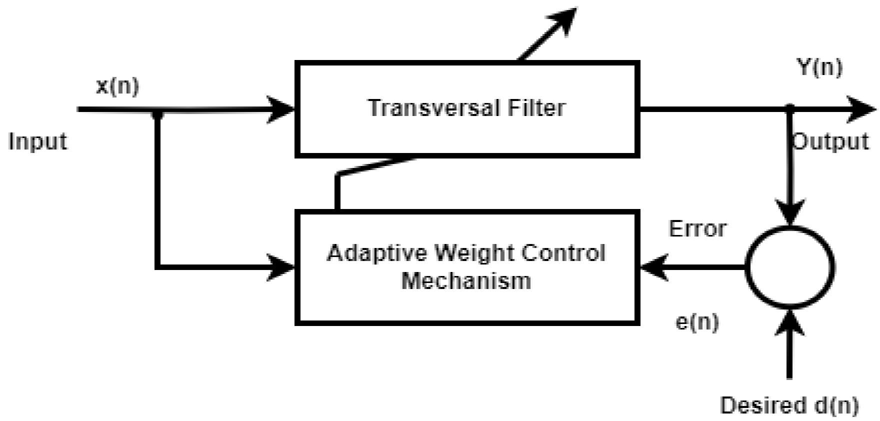

Figure 2. Functional block diagram of an Adaptive Transversal Filter

y1(n) computes output of filter in reaction to an administered input signal. e1(n) determines the approximation error by contrasting the output with the intended signal. It automatically modifies the filter parameters based on the approximation error.

2.2.1 Recursive Least Squares (RLS) filter

The Recursive Least Squares (RLS) filter is an effective adaptive filtering technique employed to minimize the weighted linear squares between the filter output and the desired signal. It continuously updates its coefficients, enabling quick convergence and exceptional performance when encountering unknown systems. RLS is recognized for its ability to handle non-stationary signals, its computational efficiency, and its effectiveness in monitoring time-varying systems.

The expression representing response of RLS filter is given by the formula:

$$y(n)=\sum_{k=0}^{n-1} w_k u(n-k) \quad (5)$$

$$e[n]=d(n)-y(n) \quad (6)$$

where,

$\boldsymbol{\xi}(w_0, w_1, w_2, \dots \dots . w_n) = \sum_0^{n-1} |e(n)|^2$,

u(n) is input signal

d[n] is desired signal

e(n) is error signal

The primary aim of the RLS filter is to decrease the weighted square error between the output and desired signals. This goal is accomplished by modifying the filter coefficients based on the prevailing error and input signal. The RLS algorithm possesses infinite memory, as it incorporates all previous input samples with suitable weighting.

The computational complexity of the RLS algorithm is relatively higher in comparison to alternative adaptive filtering algorithms due to its matrix inversion operation.

2.2.2 Least Mean Square Filters

The Least Mean Square (LMS) filter serves as an adaptive filtering methodology utilized for the estimation of unknown system parameters by minimizing the mean square error between the desired signal and the filter output. In contrast to the Recursive Least Squares (RLS) filter that possesses infinite memory capacity, the LMS filter lacks memory capability and solely focuses on the current error during its updating process.

Employing a gradient-based technique, the LMS algorithm facilitates the adjustment of its filter coefficients. The formula for updating the filter coefficients can be expressed as:

$$w_i'(\mathrm{n}) = w_{i-1}'(\mathrm{n}) + \mathrm{me(n)x(n\text{-}i)} \tag{6}$$

Where m is step size , i=0,1,….M-1, and n=0,1,2,…..,N-1.

The equation above is used to minimize the sum of squared errors(Haykin,1996).

The speed of convergence of the LMS algorithm is governed by the step size parameter μ. In cases where μ is excessively large, the algorithm might encounter instability, whereas if it is too small, the convergence process will be sluggish.

$$0 < \mu < \frac{1}{10MP_X} \tag{7}$$

where,M is the length, and Px is the power of the reference signal, which is given by

$$P_x = \frac{r_{xx(0)}}{M+1} \tag{8}$$

Where $r_{xx(0)}$ is the autocorrelation of the reference signal for zero lag.

The determination of the filter length 'M' plays a pivotal role in LMS filtering. The Minimum Description Length (MDL) criterion is commonly employed for identifying the optimal filter length. This criterion aims to strike a balance between the model's complexity and its ability to fit the data, and can be defined as:

$$MDL(M) = -L(\theta_M) + \frac{1}{2}\mathrm{MlnN} \tag{9}$$

Where M is the filter length, N is the length of the input sequence

In equation (9), the first term decreases as the filter length M increases, indicating a reduction in the model complexity. Conversely, the second term increases linearly with M, reflecting the increased description length needed to represent the model. Therefore, the Minimum Description

Length (MDL) criterion can be minimized by appropriately balancing the reduction in model complexity with the increased description length required for a longer filter length.

The flow diagram of the NavIC multipath estimation and mitigation analysis is described below is depicted in Fig.3.

Step 1: The NavIC receiver is placed in the boat. The receiver capture direct signals from the satellite and reflected signals caused by the interactions with the sea surface continuously.

Step 2: The collected raw data of NavIC signals is converted into Receiver Independent Exchange Format (RINEX) or Comma Separated Value(.CSV) file by the software IRNSSUR provided by accord. The generated files can be used for the further to estimate and mitigate the multipath.

Step 3: The Code Minus Carrier(CMC) method is utilized to determine the multipath error. This technique subtracts the carrier phase measurements from the code measurements to obtain multipath error.

Step 4: The estimated multipath signals is given as input to the filters, RLS, LMS and NLMS to separate filtered signal and error signals.

Step 5: The output signal of the adaptive filter represents the mitigated of multipath free NavIC signal. it is crucial for position accuracy.

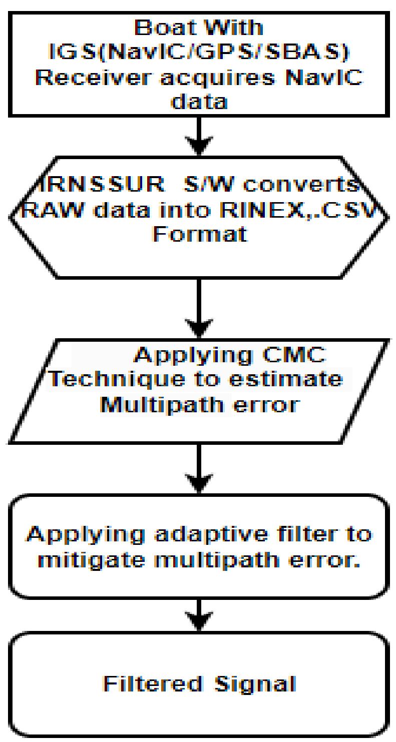

Fig.3 Flow chart of estimation and mitigation of Multipath for NavIC

3. Data Acquisition and Processing

The field trials to analyze the performance of NavIC are performed at various research organizations and academic institutions in India. However, not much significant work is carried out at marine environments. There is an indeed requirement for testing the marine environments.

Hence, for typical marine environments, Hope Island, which is 7miles away from Kakinada sea shore, Kakinada, Andhra Pradesh, India is chosen for carrying out the experiment. The receiver is carried from sea coast of Kakinada to Hope Island in a boat and also kept the receiver at static position at Hope Island. The boat travelled with an average speed of 20konts. The data is acquired continuously along the path. Along this path 5 to 7 satellites are visible. The GDOP is observed as 3.61 to 6.35, the signal intensity (Carrier-to-Noise ratio, C/No) of the satellites between 56.35dBHz to 31.25dBHz along the trajectory. The experiment set up of NavIC receiver depicted in Figure 4.

Figure.4. Experimental set-up of NavIC receiver in boat.

4. Experimental results and Discussion

The NavIC receiver experiment conducted on 2nd April 2019 at Kakinada Sea Shore, Andra Pradesh, India. The results depict to NavIC -1C are presented. Multipath on MPL5 and MPS1 are estimated as estimated as maximum 1.98m on L5 and 2.32m on S1 frequencies by using CMC method. The figures 5,6 depicts the calculated multipath error. And code multipath error was zero Mean time series signal with standard deviations of 0.4189m for MPL5 and 0.5059m for MPS1. These errors are applied to RLS, LMS, NLMS filters to mitigate of multipath, these filters providing a comprehensive analysis of their performance in mitigating multipath errors.Response of MPL5 and MPS1 are depicted in figures (7,8,9,10,11,12).

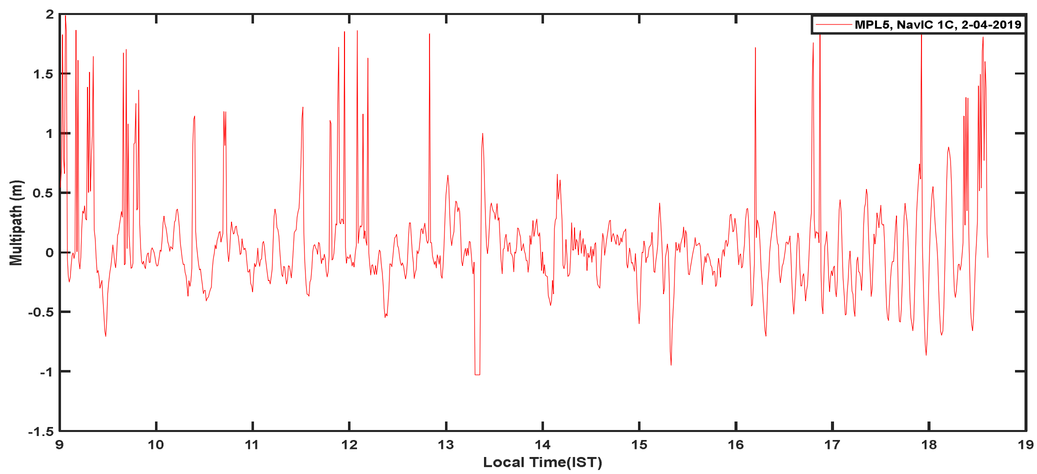

Figure.5. Estimated Multipath error on L5 (MPL5) for NavIC 1C on 2-04-2019

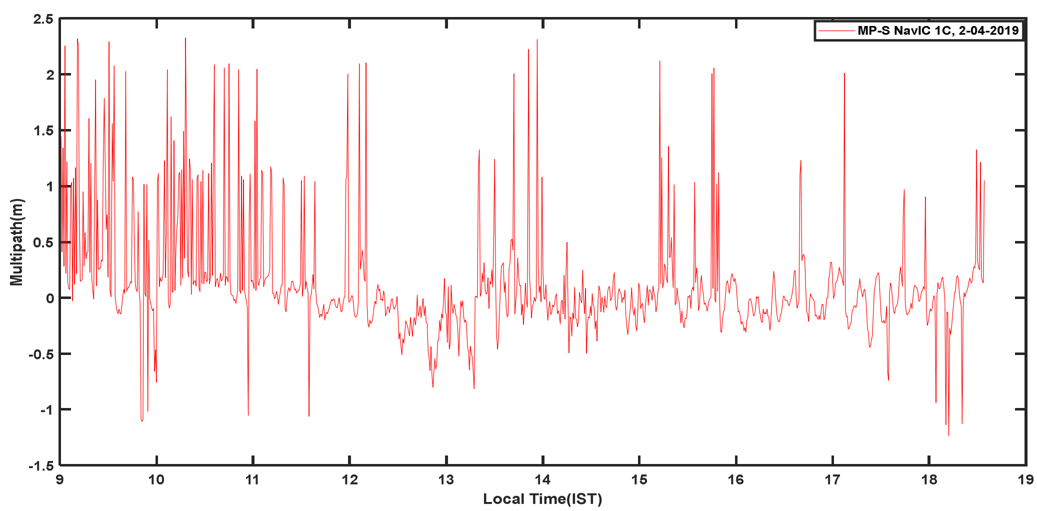

Figure 6: Estimated Multipath error on S1 (MPS1) for NavIC 1C on 2-04-2019

A. Multipath Mitigation of RLS

X(n), represents the estimated multipath error from the L5 and S1 signals, MPL5 and MPS1 respectively. To reduce the multipath error, a 32 stage FIR low pass filter with the cutoff frequency of 1Hz is designed. The output d(n) for RLS filter.

The step size parameter of RLS filter is 0.0050 for MPL5 and 0.0033 for MPS1 respectively. y(n) and e(n) will depend on the fixed steps sizes.as a result of filtering process, multipath error minimized signal standard deviation is reduced to 0.68cm from 1.98cm on L5 and reduced to .96cm from 2.32cm similarly.

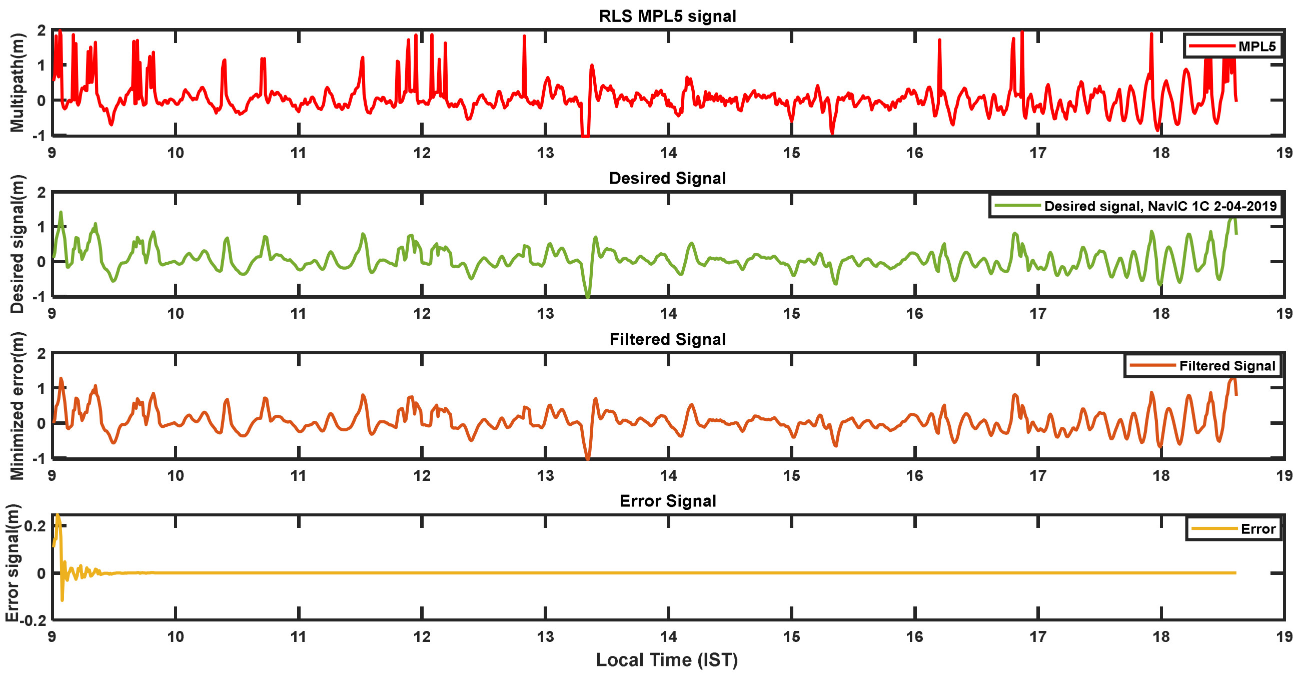

Figure 7: Mitigation of Multipath using RLS filter on L5 of 1C (2-04-2019). a) Estimated Multipath error (MPL5 Signal). b) Desired Signal. c) Filtered signal. d) Error signal.

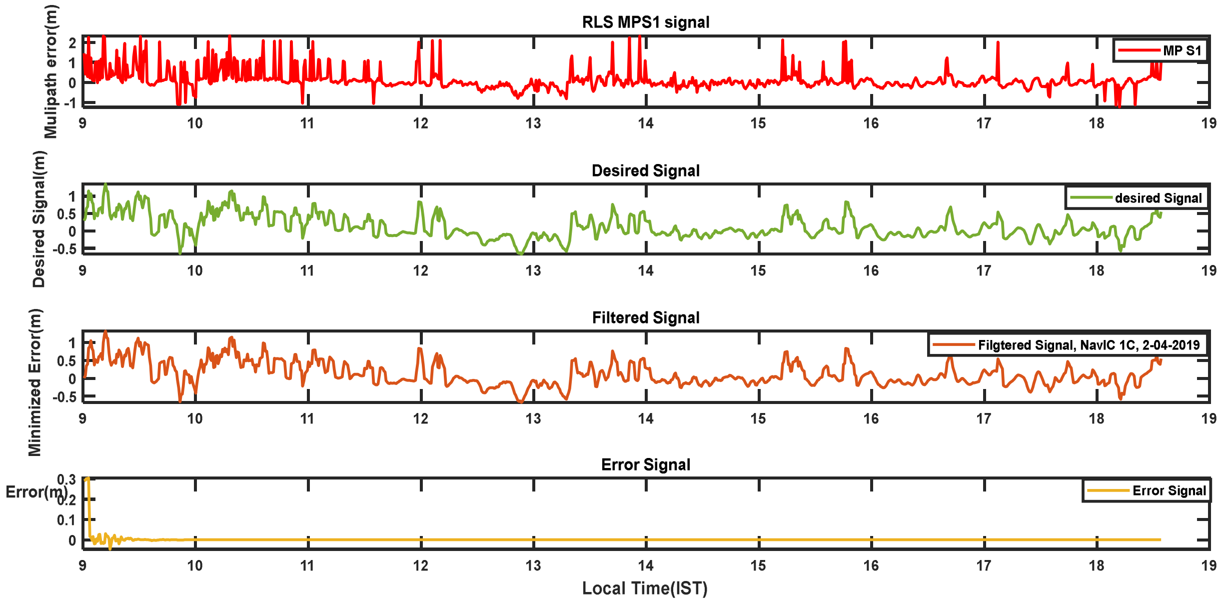

Figure 8: Mitigation of Multipath using RLS filter on S1 of 1C (2-04-2019). a) Estimated Multipath error (MPS1 Signal). b) Desired Signal. c) Filtered signal. d) Error signal.

B. Multipath Mitigation of LMS

The LMS filter uses a step size parameter is 0.0050 for MPL5 and 0.0033 for MPS1. The filter y(n) output and e(n) error signal depends on the fixed step sizes. The multipath error minimized signal standard deviation is reduced to 0.58cm from 1.98cm on L5 and reduced to .67cm from 2.32cm for S1.

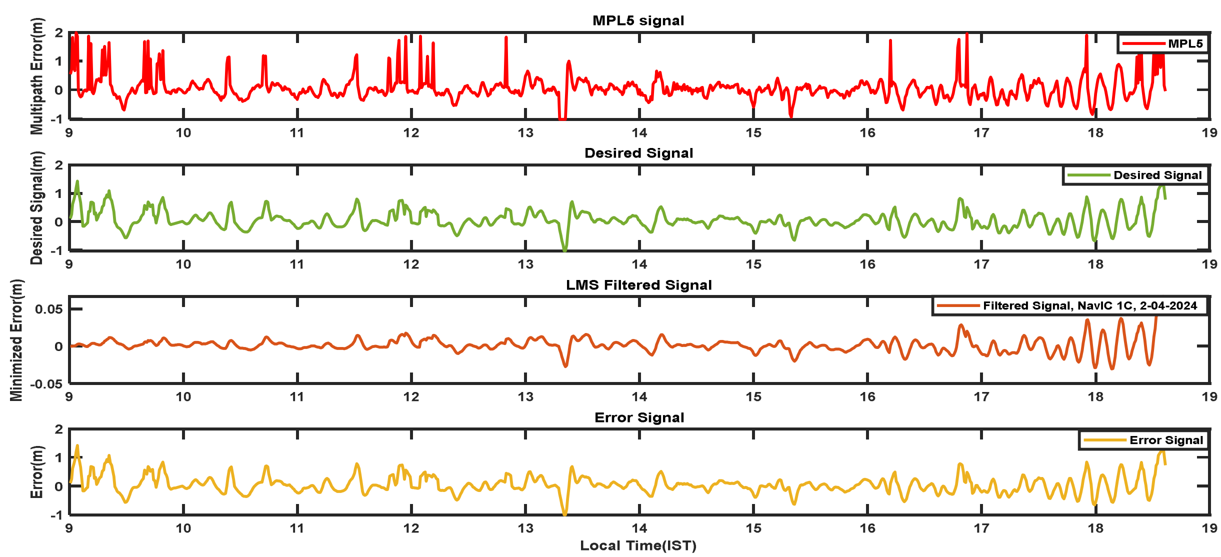

Figure 9: Mitigation of Multipath using LMS filter on L5 of 1C (2-04-2019). a) Estimated Multipath error (MPL5 Signal). b) Desired Signal. c) Filtered signal. d) Error signal.

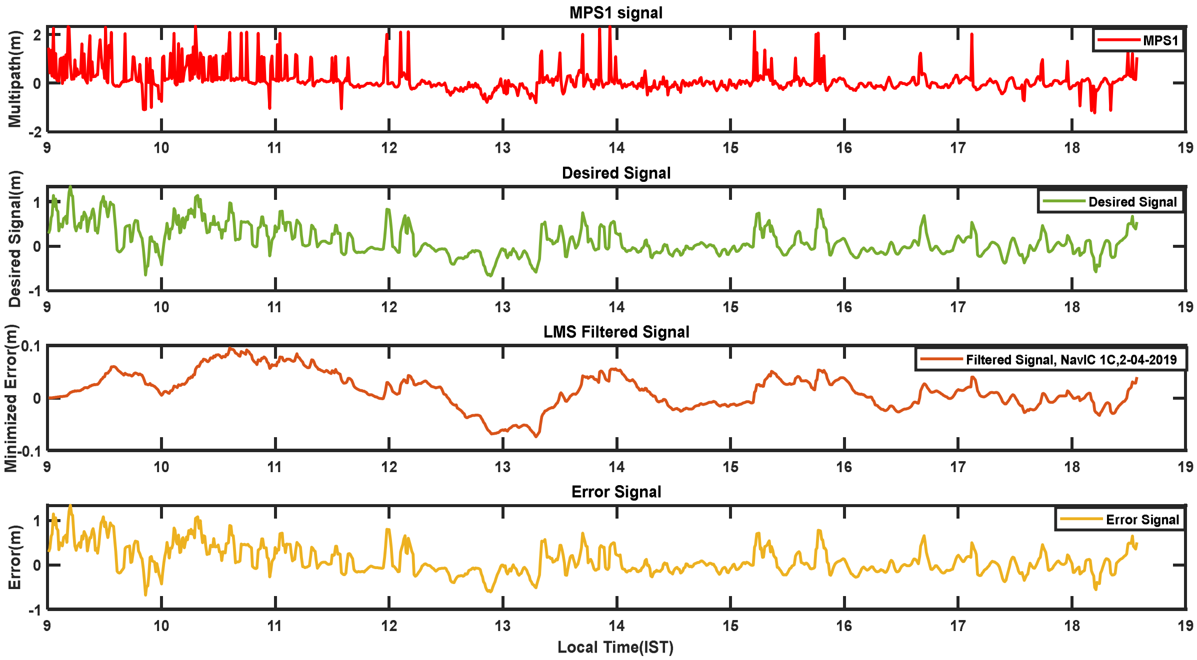

Figure 10: Mitigation of Multipath using LMS filter on S1 of 1C (2-04-2019). a) Estimated Multipath error (MPS1 Signal). b) Desired Signal. c) Filtered signal. d) Error signal.

C. Multipath Mitigation of NLMS

The Normalized Least Mean Square (NLMS) filter is a simplified and faster version of the LMS filter, offering greater stability. It is well-suited for reducing multipath errors in both static and kinematic NavIC applications. Figures 11 and 12 illustrate the response of the NLMS filter for zero-mean input signals. After applying the NLMS filter, the standard deviation (SD) is reduced to 1.2 cm from 22 cm, representing a significant 99% enhancement in multipath error reduction efficiency.

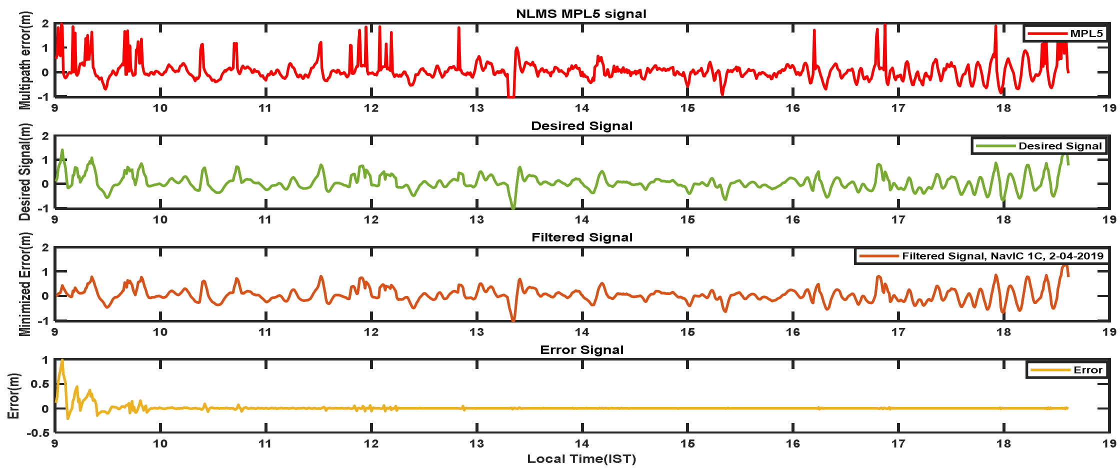

Figure 11: Mitigation of Multipath using NLMS filter on L5 of 1C (2-04-2019).
a) Estimated Multipath error (MPL5 Signal). b) Desired Signal. c) Filtered signal. d) Error signal.

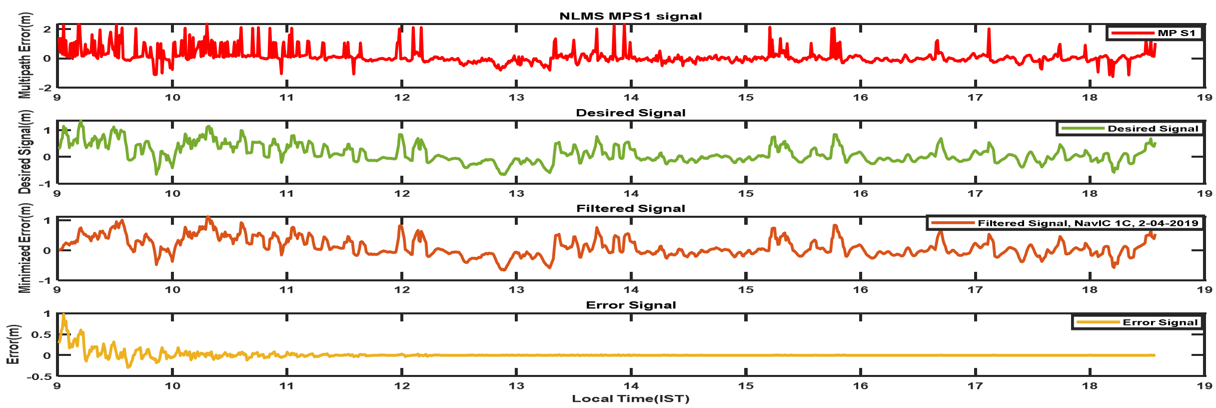

Figure 12: Mitigation of Multipath using NLMS filter on S1 of 1C (2-04-2019).
a) Estimated Multipath error (MPL5 Signal). b) Desired Signal. c) Filtered signal. d) Error signal.

S.No	Filters	Multipath	STD before mitigation	STD after mitigation	% Improvement
1	RLS	L5(MPL5)	0.41	0.06	85.3
	LMS			0.01	97.5
	NLMS			0.007	98.29
2	RLS	S1(MPS1)	0.51	0.06	88.23
	LMS			0.02	96.07
	NLMS			0.005	99

$$\%\text{Improvement} = \frac{a-b}{a} X\ 100 \quad (10)$$

σ = Standard deviation

a = Standard deviation before multipath

b = standard deviation after multipath

The efficiency of the adaptive filter technique depends on percentage improvement. To evaluate the filter performance Eq. (10) is used to find percentage improvement. The standard deviation is calculated as 0.41 before the mitigation. After applying the RLS filter, the standard deviation is reduced from 0.41 to 0.06 and the 85.3% of mitigation is achieved on L5 frequency. The standard deviation for LMS filter changes from 0.41 to 0.01 after applying the filter and achieves 97.5% of multipath mitigation on L5 frequency. The NLMS filter reduces effectively and it mitigates the multipath by 98.29% on L5 frequency.

Conclusions

The investigation aimed to estimate multipath errors using the Code Minus Carrier Technique. It was found that the multipath error reached a maximum of 1.98cm for L5 and 2.32cm for S1 frequencies. These errors were then converted into zero-mean time series signals, with standard deviations of 0.4189m for L5 (MPL5) and 0.5059m for S1 (MPS1). These multipath error signals were fed into adaptive algorithms to mitigate the multipath errors. The Recursive Least Squares (RLS) filter showed an 88% improvement in reducing errors. In comparison, the Least Mean Squares (LMS) and Normalized Least Mean Squares (NLMS) filters performed even better, achieving error reductions of 97.5% and 99%, respectively. The LMS filter was noted for its simpler design, faster response, and increased stability compared to the RLS method. Conversely, the NLMS filter demonstrated versatility, making it suitable for both static and kinematic NavIC applications, and therefore a preferred choice for multipath mitigation.

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