Enhanced GNSS Signal Tracking in Fading Environments using Frequency Diversity

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ABSTRACT: A new methodology to enhance the GNSS parameter estimation accuracy in multipath fading environments using the frequency diversity reception is proposed herein. In such environments, fading occurrences observed in different frequency bands are independent of each other. Characteristics of frequency diversity reception using GPS L1 and L2C signals in dense fading conditions are first discussed and compared with those of spatial diversity reception. Comparative analyses of characterization metrics between frequency diversity and spatial diversity signals support the argument that the former is as effective as the latter. A frequency diversity based combined tracking approach is then proposed, and the performance is evaluated using the data collected in dense foliage and residential environments. Results show that frequency diversity based combined tracking results in improved performance compared to that of single frequency tracking. 3D position error reduction achieved by the proposed method is 52% in foliage conditions and 50% in residential environments. Copyright © 2017 Institute of Navigation

INTRODUCTION

The multipath issue remains a topic of great importance in the Global Navigation Satellite System (GNSS) community. As a result of constructive and destructive interference of multipath components on the Line-of-Sight (LOS) signal, the signal power undergoes temporal and spatial fluctuations, a phenomenon called fading. The signal fading has two major impacts on the receiver performance, namely increase in GNSS measurement estimation errors and discontinuity in measurement generation. The latter is caused by deep signal fading which causes frequent losses of lock in tracking. A tremendous amount of research has been performed towards improving the sensitivity of GNSS receivers to combat the fading effect, such as [1–3]. Some research focus on diversity combining techniques to enhance the processing gain. For example, [4, 5] employed polarization diversity, while [6] used spatial diversity to enhance detection performance. [7] discussed parameter estimation enhancement achieved through closed loop tracking using the spatial diversity reception. Given the availability of emerging new civilian signals at different frequencies, frequency diversity reception can be employed in various fading environments. The potential signal decorrelation between signals at different frequencies adds another dimension to diversity reception techniques. This work focuses on two parts, namely (a) characterizing the fading behavior of multi-frequency signals in harsh fading environments and (b) employing frequency diversity to improve tracking performance. The following sections discuss the contributions and limitations of previous work in terms of multi-frequency fading characterization and frequency diversity based combined tracking.

Statistical fading models in wireless channels are investigated by many authors in terms of signal power distribution, Doppler spread, Angle-of-Arrival spread, and second order statistics such as Level Crossing Rate (LCR) and Average Fading Duration (AFD) [8, 9]. However, the suitability of a specific statistical model depends on several assumptions, such as the scattering scenario (presence of Non-LOS, Non-LOS only, or mixture of LOS and Non-LOS), relative dynamics of the transmitter and receiver, and characteristics of the propagation medium (ionosphere, rain). Empirical models are discussed by [10–12] using the actual data. [13] discusses analytic expressions for Time-of-Arrival Probability Density Function (PDF) for GPS signals.
[14] provides a detailed analysis of first and second order fading statistics of channel characterization for GPS L1 signals in different indoor and outdoor environments. The spatial diversity reception and its benefits are characterized in [6]. Although spatial diversity reception produces uncorrelated signals, it requires several antennas, which increases the receiver size, cost, and complexity. In frequency diversity reception, a single antenna can be employed to receive multi-frequency uncorrelated signals; therefore, the receiver size can be reduced. However, fading characteristics of multi-frequency GNSS signals in harsh environments are limited in literature. Introduction of GPS block IIR (M) and block IIF satellites is resulting in the transmission of modernized navigation signals. These signals include L2C (transmitted from both IIR-M and IIF blocks) and L5 (transmitted from IIF block) signals. The L2C signal consists of two sub-signals, namely the Civilian Moderate (CM) and Civilian Long (CL, which is a pilot) signal. L2C signals are 1.5 dB weaker than L1 C/A and L5 in-phase signals are stronger by 0.6 dB compared to L1 C/A signals in block IIF satellites [15, 16]. Since the frequency differences between these frequencies are low, the process of multi-frequency signal combining directly at the correlator level would enhance the effective Signal-to-Noise Ratio (SNR). If the signals are uncorrelated (fluctuate independently) in fading environments, then the weaker signal would benefit from the stronger signal due to the combining process. Also, IIR-M and IIF block satellites constitute more than 50% of the satellites in the GPS constellation. Hence, there exists a potential to exploit frequency diversity combining. Before doing so, it is important to understand the benefits of combining independent signals received at different frequencies (defined herein as multi-frequency signals), which requires the knowledge of their fading behavior. Hence, the first part of the paper investigates fading characteristics of the L2C and L1 C/A signals. These characteristics are compared with those of single-frequency spatial diversity reception.

Many researchers have proposed algorithms and methods for the independent or combined acquisition and tracking of modernized multi-frequency GPS signals [17–21]. In general, signal combining can be implemented at different levels of a GNSS receiver, namely at the correlator level, discriminator level, measurement level, or position level. [18] proposed a Kalman Filter (KF)-based combined tracking to estimate the ranging parameters. The combining was made at the discriminator level wherein the discriminator outputs were applied to KF, and tracking performance was evaluated in signal attenuated conditions rather than in fading conditions. [20] proposed a similar KF-based combined tracker for GPS L1/L5 signals; although the measurement model included the correlation values from L1 and L5 signals, no correlator level combining was performed. Also, a ten-state KF is required for each PRN, which increases the computation burden; in addition, performance evaluation was limited to simulated scenarios. [21] proposed a multi-frequency vector tracking loop architecture to enhance carrier phase tracking under scintillation fading conditions. It is an extension of the Vector Delay and Frequency Lock Loop (FLL)-based architecture applied to L1 C/A and L2C tracking. The navigation filter in Vector Delay and FLL receives correlation values from multi-frequency signals from all the satellites and tracks their code and frequency jointly.

Nonetheless, combining multi-frequency signals at the discriminator or measurement levels might not be fully beneficial if the power values of individual signals drop below the tracking threshold. In this case, the tracking process would be discontinuous; therefore, the benefits of multi-frequency combining would not be fully exploited. However, if the diversity signals are combined directly at the correlator level, then a resulting signal with enhanced SNR can be produced and can then be used to estimate the parameters of individual signals. Hence, there exists a potential advantage in combining the uncorrelated multi-frequency signals directly at the correlator level. Therefore, the second part of the paper proposes a combined tracking approach based on correlator level combining of independent signals observed at different frequencies. The combined tracking involves a single loop to track both L1 and L2 signals.

**METHODOLOGY**

The methodology used for frequency diversity characterization is discussed first, followed by the tracking approach based on correlator level frequency diversity combining.

**Frequency Diversity Characterization**

Different metrics, namely C/N0, correlation coefficient, AFD, and LCR are used to characterize diversity signals. The correlation coefficient is a metric to quantify the similarities between two random variables. The correlation coefficient can be characterized either by the envelope or the complex representation of input signals [20]. In this research, the independent signal reception in fading environments is evaluated empirically by comparing the complex correlation coefficients between frequency diversity and spatial diversity branches, that is, the complex correlation coefficient of L1 and L2C signals (frequency diversity pair) received by
the same antenna is compared with that of two L1 signals received by two separate antennas (spatial diversity pair). In addition, the AFD and the LCR metrics, which are second order statistics, are considered to characterize frequency diversity. LCR defines the average rate (events/second) at which the signal crosses a given threshold downward. AFD is the average time (in seconds) that the signal stays below a given threshold [14].

**Frequency Diversity Tracking**

The pilot signal is dataless; therefore, it supports longer coherent integration and pure Phase Lock Loop (PLL) tracking which provides significant improvement under weak signal condition. However, receiver clock quality and user dynamics (pedestrian) restrict an increase in the coherent integration time. Moreover, under harsh fading conditions (as explained later), PLL would not be able to maintain coherent phase tracking. Therefore, pure PLL tracking using only the pilot channel is not helpful under aforementioned conditions and hence was not considered in this research.

This section discusses the proposed closed loop tracking approach using the combined signal. The core objective is to combine the correlation values from L1 and L2 diversity branches. PLL often fails to maintain perfect synchronization in harsh fading. This means that the phasors of L1 \((I_{L1} + jQ_{L1})\) and of L2 \((I_{L2} + jQ_{L2})\) rotate at different angular rates. Also, the PLL is more prone to frequent losses of lock in harsh conditions. Hence, coherent combining of correlation values from diversity branches is challenging to achieve. The correlation power outputs from two signals are therefore combined non-coherently at the post-correlation stage, and the combined signal is tracked with non-coherent discriminators in FLL and Delay Lock Loops (DLL). The FLL and DLL use conventional discriminators whose inputs are the non-coherent diversity combined signals. Details of FLL and DLL are provided in the following sections.

The FLL uses a single discriminator and loop filter to track the Doppler associated with the combined signal. It is implemented using the Power Difference (PD) non-coherent discriminator. The PD discriminator was introduced by [22] and was extensively investigated by [23]. The steady state and transient response performance of the PD discriminator is poor compared to the traditional \(\text{atan}\) phase difference discriminator or the cross product discriminator for moderate to high \(\text{C/N}_0\) values. However, in weak signal conditions, it is more robust than the traditional discriminators in terms of sustaining loop lock [23, 24]. Hence, it is justifiable to use the PD discriminator in harsh fading environments where \(\text{C/N}_0\) values can fade as low as 15 dB-Hz. The FLL herein uses a second order loop filter [25]. The PD FLL discriminator uses correlation values from three frequency bins, namely one set from the frequency bin being tracked (sync) and two sets from the adjacent fast and slow frequency bins. The \(\text{sync, fast, and slow}\) coherent correlation values for L1 or L2 signals can be expressed as

\[
P_{\text{sync}}^{L_i} = \sqrt{C_{L_i} R_{L_i}(\tau)} \sin \left( \frac{\delta \omega_{L_i} T_c}{2} \right) \exp \left( j \delta \theta_{L_i} \right) + n_{\text{sync}}^{L_i} \tag{1}
\]

\[
P_{\text{fast}}^{L_i} = \sqrt{C_{L_i} R_{L_i}(\tau)} \sin \left( \frac{\delta \omega_{L_i} + \Delta \omega_{L_i} T_c}{2} \right) \exp \left( j \delta \theta_{\text{fast}} \right) + n_{\text{fast}}^{L_i} \tag{2}
\]

\[
P_{\text{slow}}^{L_i} = \sqrt{C_{L_i} R_{L_i}(\tau)} \sin \left( \frac{\delta \omega_{L_i} - \Delta \omega_{L_i} T_c}{2} \right) \exp \left( j \delta \theta_{\text{slow}} \right) + n_{\text{slow}}^{L_i} \tag{3}
\]

where the subscript \(L_i\) indicates the signal type, L1 or L2; \(\delta \tau_{L_i}, \delta \omega_{L_i}\), and \(\delta \theta_{L_i}\) are the difference between the code phase, Doppler frequency, and carrier phase of incoming and local replica signal; noise terms \(n_{\text{sync}}^{L_i}, n_{\text{fast}}^{L_i}\), and \(n_{\text{slow}}^{L_i}\) are zero mean complex Gaussian processes and are correlated as 

\[
E \left[ n_{\text{fast}}^{L_i} n_{\text{sync}}^{L_i} \right] = \frac{\sigma^2}{\eta} \sin(\Delta \omega T_c) \text{; } C_{L_i} \text{ is the total received power; } R_{L_i} \text{ is the Auto Correlation Function; and } T_c \text{ is the coherent integration time. In the term } \Delta \omega_{L_i} = 2 \pi \Delta f_{LL_i}, \text{ } \Delta f_{LL_i} \text{ is the frequency spacing (in Hz) between the sync and fast (or slow) frequency bins. Note that for the L2 signal, frequency spacing } \Delta f_{LL_2} = (f_{L2}/f_{L1}) \text{.}
\]

\bullet \text{A}_{LL_1}, \text{where the scale factor } (f_{L2}/f_{L1}) \text{ is the ratio of center frequencies of the L2 and L1 signals (1227.6/1575.42). The purpose of choosing the frequency spacing } \Delta f_{LL_2} \text{ in L2 as a scaled factor of that of L1 is explained later.}

The FLL first outputs the Doppler corresponding to the L1 frequency \((f_{dL_1})\) using the combined signal, \(f_{dL_1}\) is then scaled by \((f_{L2}/f_{L1})\) to obtain the Doppler of the L2 frequency \((f_{dL_2})\). This method of obtaining L2 Doppler by scaling the L1 Doppler is implemented in [18].

The modified form of PD discriminator [22] estimating the unfiltered frequency error \(f_{dL_1}\) associated with \(f_{dL_1}\) using the combined signal is expressed as

\[
f_{dL_1} = \frac{\left( S_p^{\text{fast}} - S_p^{\text{slow}} \right)}{T_c S_p^{\text{sync}}} \left( \frac{\Delta \omega_{L_1} T_c}{2} \right) \left( 1 - \cos(\Delta \omega_{L_1} T_c) - \frac{\Delta \omega_{L_1} T_c}{2} \sin(\Delta \omega_{L_1} T_c) \right) \tag{4}
\]
\[
S_P^{fast} = w_1 |P_{L1}^{fast}|^2 + w_2 |P_{L2}^{fast}|^2 \text{ is the combined fast power}
\]
\[
S_P^{slow} = w_1 |P_{L1}^{slow}|^2 + w_2 |P_{L2}^{slow}|^2 \text{ is the combined slow power}
\]
\[
S_P^{sync} = w_1 |P_{L1}^{sync}|^2 + w_2 |P_{L2}^{sync}|^2 \text{ is the combined sync power}
\]

Weights \(w_1\) and \(w_2\) decide the type of combining, namely selection, Equal Gain Combining (EGC), or Maximum Ratio Combining (MRC). In the selection combining, only one signal with maximum power is selected with its weight equal to one. The weights of other signals are zero. In EGC, \(w_1 = w_2 = 1\). Weights for MRC are computed based on the SNR of individual signals as given in [26].

The DLL uses the traditional Early-Minus-Late Power (EMLP) discriminator [25] and operates in carrier-assisted mode with a 1st order filter [25]. The EMLP discriminator for the DLL is expressed as

\[
\hat{c} = \left(1 - \frac{CS_{EL}}{2}\right) \cdot \left(\frac{S_{fast}^{sync} - S_{slow}^{sync}}{S_{fast}^{sync} + S_{slow}^{sync}}\right)
\]

Inputs for DLL are the early and late combined correlation power values of L1 and L2 from their respective sync frequency bins, that is, \(S_{fast}^{sync}\) and \(S_{slow}^{sync}\). They are expressed as

\[
S_{fast}^{sync} = w_1 |P_{L1,early}^{sync}|^2 + w_2 |P_{L2,early}^{sync}|^2 \text{ is the combined early power}
\]
\[
S_{slow}^{sync} = w_1 |P_{L1,late}^{sync}|^2 + w_2 |P_{L2,late}^{sync}|^2 \text{ is the combined late power}
\]

\(CS_{EL}\) is the chip spacing between early and late correlators.

The L2 correlation value, \(P_{L2}\) is obtained by summing the L2CM and L2CL correlation values, that is, \(P_{L2} = (I_{L2CM} + jQ_{L2CM}) + (I_{L2CL} + Q_{L2CL})\) for every coherent integration time \(T_c\). The L2CL signal’s correlation values are corrected for L2 navigation bits by performing single-bit data estimation. Coherent combining of CM and CL values enhances the \(P_{L2}\) power by about 3 dB. This makes the theoretical LOS power of L2 lower than that of L1 only by about 1.5 dB.

Figure 1 shows the Cross Ambiguity Function (CAF) functions for L1 and L2 signals in the Doppler and delay domain. The CAF is a two-dimensional profile of the signal’s correlation power values as a function of delay and Doppler values. The correlator locations are indicated by green dots. In the Doppler domain CAF, the frequency spacing for L2 correlators is the scaled ratio (ratio of center frequencies, \(f_{L2}/f_{L1}\)) of that of L1. This ratio is maintained in order to achieve comparable correlation power outputs in two signals. The relative difference between the scaled carrier Doppler values of the two signals due to ionospheric propagation is very small, namely on the order of mHz [27]. This offset is negligibly small compared to the null width of the Doppler Domain CAF (100 Hz for \(T_c \approx 20\) ms); hence, it can be ignored while combining the correlation power values. The tracker involves a power combiner where the L1 correlator power values (fast, sync, slow, early, and late) are combined non-coherently with those of L2 with appropriate weights. The combined power values are then passed to the respective non-coherent discriminators which are followed by the loop filters. The FLL uses a second order filter and the assisted DLL uses a first order filter.

**DATA COLLECTIONS**

Two data sets were collected. The first set was collected in a dense indoor shopping mall environment to characterize and demonstrate the diversity nature of dual frequency reception. The
second set was collected in two different pedestrian fading environments to analyze the performance of the proposed tracking method. Descriptions of these test environments are given in Table 1.

**Data for Frequency Diversity Characterization**

This data was collected in an indoor shopping mall. Data collection environments and the sky plots of the selected PRNs at the time of collection are shown in Figure 2. Blue circles show selected PRNs that transmitted L1 and L2C signals. A reference rover architecture was considered, where a reference receiver located in an open-sky location was used to obtain the code Doppler, carrier Doppler, and corresponding GPS time tags, which were used to aid the signals from the rover antennas to generate the (I, Q) correlation values. The L1 and L2 data bits extracted from the reference antenna were used for extended bit integration to get the best estimate of $C/N_0$ in harsh fading conditions. Two dual-frequency NovAtel GPS-702-GG antennas were used as rover antennas. The second rover antenna was located 20 cm away from the first antenna to provide sufficient signal decorrelation in the spatial domain. Here, the L1 and L2 signals from the first rover antenna form the frequency diversity pair, and the L1 signals obtained from the two rover antennas form the spatial diversity pair. Thus, spatial diversity characteristics can be compared with those of frequency diversity using this set-up. The five RF branches (two from the reference antenna and three from rover antennas as shown in Figure 2) were fed to the synchronized channels of the National Instrument front-end; this data is referred to as *Indoor Data* in subsequent sections.

**Data for Frequency Diversity Tracking**

Two pedestrian data sets were collected in different fading environments on the campus of the University of Calgary. This data is referred to as *Pedestrian Data 1* and *Pedestrian Data 2*. Descriptions are given in Table 1. Figures 3 and 4 show the two environments and the sky plots of selected PRNs (in blue circles) at the time of data collection. All selected PRNs transmitted both L1 and L2C. The true pedestrian trajectory is shown in red color within the overlapped Google Earth image of the environments. Figure 3 shows the pedestrian carrying the test equipment. The test equipment used for the data collection involved a

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Table 1—Selected fading environments

<table>
<thead>
<tr>
<th>Data</th>
<th>Description of fading environment</th>
<th>IIR-M/IIF PRNs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor data: Shopping</td>
<td>Typical North American shopping mall with three floors. Data used to demonstrate the diversity nature of dual frequency reception.</td>
<td>6, 12, 17, 24</td>
</tr>
<tr>
<td>Pedestrian data 1: Dense foliage</td>
<td>Environment consists of dense spruce trees. Pedestrian walked along tree shadows in a repetitive north-south motion (Figure 3).</td>
<td>6, 12, 24, 25</td>
</tr>
<tr>
<td>Pedestrian data 2: Pathway near a residential area</td>
<td>Pathway surrounded by a seven-story building, trees, and other small buildings (Figure 4). Pedestrian Data 1 and 2 are used to analyze the performance of proposed tracking method.</td>
<td>6, 12, 17, 24</td>
</tr>
</tbody>
</table>

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![Fig. 2—Indoor data collection environment (left) and sky plot (right).](Image)
NovAtel GPS-702-GG dual frequency antenna to collect L1 and L2 signals that were sampled by a TeleOrbit RF front-end. The reference trajectories were determined using a NovAtel SPAN-LCI™ system, also later used to derive the reference signal parameters (true Doppler, range, and position). The performance analysis includes comparison of 3D position and velocity estimates. Additional PRNs that transmitted only L1 signals were also considered to estimate these states, for example, PRN02 and PRN10 in Pedestrian Data 1, PRN02 in Pedestrian Data 2.

ANALYSIS

Spatial Diversity Versus Frequency Diversity Characterization

Signal Strength

C/N₀ plots from the static data collection in the shopping mall are shown in Figure 5. The signals ‘Antenna1 L1’ and ‘Antenna2 L1’ form the spatial diversity pair and ‘Antenna1 L1’ and ‘Antenna1 L2’ form the frequency diversity pair. The fading phenomenon is evident for rover signals from various PRNs. The destructive and constructive fading in two signals (Antenna1 L1 and Antenna1 L2) occur at different instances, an observation also seen for spatial diversity signals. The plots show that the signal strengths of L1 and L2C vary independently in the given fading environment. Depending on the signal visibility and the amount of fading, the power difference can vary from 5 to 25 dB. Such independent fluctuations were also observed in indoor dynamic tests (speed ~10 cm/s) in both frequency and spatial diversity reception.

Complex Correlation Coefficient, AFD, and LCR

In this section, the diversity reception between frequency and spatial diversity is compared using the complex correlation coefficient, AFD, and LCR metrics. The complex correlation coefficients for different PRNs for indoor static tests are given in...
Table 2. These values are obtained from the complex representation of the respective signals, that is $I + jQ$, after the data bit wipe-off process. The L1 and L2 terms in the table correspond to the L1 and L2C signals from Antenna1 and the L1' term corresponds to the L1 signal from Antenna2. As it is evident from comparing the correlation coefficient values, frequency diversity reception can be as independent as spatial diversity reception in most cases in this data set. However, in some cases, such as PRN24, the L2 signal is more correlated to L1 than the spatial diversity branch (L1'). This is also observable in the C/N0 values of Figure 5.

Figure 6 shows the AFD and LCR plots for the indoor static case. AFD and LCR are a function of signal threshold. AFD increases as the signal threshold increases. LCR has a typical ‘bell’-shaped curve whose width ranges from 5 to 25 dB. This indicates the range of power fluctuations occurring in different signals. For a given threshold, AFD is much higher for the static case than that of the dynamic case. For instance, for a 20 dB-Hz threshold, the static AFD is 10 s whereas in dynamic tests it is observed to be 2 s. This is attributed to the rapid signal fluctuations that occur in a receiver moving in a multipath environment. Likewise, the LCR values for the dynamic case are higher than those of the static case for all PRNs. The most interesting observation is that the AFD and LCR of L2 signals (Antenna1 L2) are more or less similar to those of their spatial diversity counterparts (Antenna2 L1). Hence, the fluctuation rate and the fade durations in frequency diversity reception can be similar to that of the spatial diversity reception.

Frequency Diversity Gain

It is also worthwhile to investigate and compare the frequency diversity gain with spatial diversity gain that can be expected in a harsh fading environment. This is investigated for the aforementioned indoor data. The post-correlation power outputs ($I^2 + Q^2$) from L1 and L2 are combined non-coherently with EGC and the post-correlation SNR (deflection coefficient) gain is evaluated for each epoch. Ideally, the gain introduced by the front-end for two diversity branches should be identical. However, this is not the case as the LNA and intermediate amplifier used for two channels belong to separate hardware blocks. Even if the input SNRs are the same, the accumulated correlation values of one of the branches may be high compared to the other. This makes the branch having higher amplifier gain to unnecessarily dominate the combining process. This issue is taken care by pre-recording the noise floors in the two channels, which will also be different depending on the amplifier gain (channel with high gain has a higher noise floor). The IF samples from one of the channels are then pre-processed by scaling them with the ratio of the pre-recorded noise floor values.

The post-correlation SNR gain obtained from two types of diversity combining are shown in Figure 7 for the indoor static case. The SNR gain is calculated with respect to the single frequency (L1) SNR. The figure shows a significant amount of SNR gain at some epochs for both types of diversity combining for all PRNs. Frequency diversity combining results in 10 to 25 dB of gain at the epochs when L1 was in deep fade in some PRNs. The SNR gain obtained by frequency diversity combining in the dynamic test (10 cm/s) is also in the range of 10 to 20 dB during L1 fading. Since the frequency and spatial diversity signals fade independently, their SNR gain values cannot be compared epoch by epoch. Nonetheless, the overall observation is that the SNR gain from the frequency diversity combining is comparable to that of the spatial diversity combining in most of the epochs. An average gain in the range of 3 to 5 dB is achieved in each case for different PRNs.
Observations obtained from the characterization show that signals in frequency diversity reception have similar characteristics as those in spatial diversity reception. This has a profound effect in reducing the receiver size and hardware requirements when compared to that of the spatial diversity reception while achieving similar benefits. Hence, this section discusses the performance of a proposed closed loop tracking approach based on frequency diversity combining.

Carrier tracking performance is analyzed by comparing the estimated L1 and L2 Doppler values obtained from the following configurations, namely (a) single frequency processing (L1 and L2 signals tracked independently) and (b) the proposed $L1 + L2$ Correlator Level (CL) combined tracking. Both configurations use the same type of discriminator (PD), loop filter, and loop update rate in order to observe the enhancement introduced due only to the diversity combining. In the latter case, two types of CL combining are tested, namely

![Graphs showing tracking performance](Image)

*Fig. 6—LCR (top) and AFD (bottom) for static Indoor Data. (Color figure can be viewed at wileyonlinelibrary.com and www.ion.org)*
EGC and MRC. [23] suggests that the value of frequency spacing between sync and fast (or slow) should be chosen such that the discriminator’s linear region is maximum while incurring minimum loss in Gain-to-Noise ratio of the PD discriminator for a given signal operating condition. Therefore, the spacing \( \Delta f_{L1} \) in the L1 branch is chosen as 20 Hz for \( T_c = 20 \text{ ms} \), such that the \( \Delta\theta_{L1} T_c \) value is about 2.5 for which the Gain-to-Noise Ratio incurs less than 1 dB loss for \( C/N_0 \) values ranging from 20 to 35 dB-Hz [23]. The frequency spacing, \( \Delta f_{L2} \), between fast and slow correlator bins in the L2 branch is therefore about 15 Hz, according to the equation \( \Delta f_{L2} = (f_{L2}/f_{L1}) \Delta f_{L1} \). The Early-Late chip spacing in the DLL discriminator, \( C_{SEL} \), is chosen as 0.15 chips.

In addition, to conduct a rigorous evaluation of the proposed CL combining scheme using the PD discriminator, the following configurations are also evaluated, namely (c) conventional atan(cross/dot) FLL discriminator [25, 28] operating on single frequency and (d) Discriminator Level (DL) combining of atan(cross/dot) discriminator (referred herein as \( x-d \) discriminator) outputs. In the DL combining, the outputs from \( x-d \) discriminators in L1 and L2 carrier branches are combined as follows:

\[
\Delta \hat{f}_{L1} = w_1 \Delta f_{L1} + w_2 (f_{L1}/f_{L2}) \Delta f_{L2}
\]
\[
\Delta \hat{f}_{L2} = w_1 (f_{L2}/f_{L1}) \Delta f_{L1} + w_2 \Delta f_{L2}
\]

where \( w_1 \) and \( w_2 \) are the appropriate weights based on the type of diversity scheme combining (EGC or MRC). The resulting carrier errors from L1 and L2 branches (\( \Delta \hat{f}_{L1} \) and \( \Delta \hat{f}_{L2} \)) are then passed to the respective loop filters.

In a similar fashion, the code Doppler estimation errors are obtained from the aforementioned configurations (a, b, c, and d) with carrier-assisted DLLs and EMLP discriminators. In this case, all the configurations use the same loop filter parameters and loop update rates. In the DL combining (configuration-d), the outputs from EMLP discriminators in L1 and L2 code branches (\( \Delta \hat{c}_{L1} \) and \( \Delta \hat{c}_{L2} \)) are combined as follows to generate the resultant code error:

\[
\Delta \hat{c} = w_1 \Delta \hat{c}_{L1} + w_2 \Delta \hat{c}_{L2}
\]

The tracking performance is also evaluated by comparing number of lock losses, Mean Time to Lose Lock (MTLLL), and Mean Signal Gap (no tracking).

The coherent integration time for L1 and L2 is 20 ms for both data sets. The L2CM and L2CL correlation values are first combined coherently. Since the L2CM changes its polarity for every CNAV data transition [29], the knowledge of CNAV data bits is necessary for the coherent combining of L2CM and L2CL, even for 20 ms integration. In this research external CNAV data bit aiding is not considered; instead, single-bit data estimation is performed by checking the coherent L2 power (L2CM + L2CL) for two polarities of L2CM. The coherent L2 power is combined non-coherently with that of L1.

In the following figures, the time scale in the x-axis starts from a point when the tracking loop enters into a \( L1 + L2 \) combined tracking state. Initial ephemeris extraction occurs in an open-sky location for about 30–40 s using the L1 signal alone; this is not shown in the figures. In order to investigate the signal strength decorrelation between the L1 and L2 frequencies in the above pedestrian data, the \( C/N_0 \) plots for all IIR/MIF PRNs are analyzed. The independent signal fluctuations are predominant in faded sections of the data. For example, it can be observed in the case of PRN 25 between 135 and 160 s (Figure 8) that the signal strengths of L1 and L2 do not vary similarly, and the highest \( C/N_0 \) values are comparable to each other. In some cases, the L2 power is higher by up to 8 dB than that of L1.

Figure 8 shows the estimated L1 carrier Doppler for PRN 25 for Pedestrian Data 1 during a harsh fading window. The true Doppler is obtained by processing the IPR samples using the software receiver GSNRx-SS™ [30], which uses information from the true receiver position. True receiver position and velocity is obtained using NovAtel SPAN-LCI™ system. The figure shows the ‘True’ Doppler plot in green. Fluctuations in Doppler frequency are caused as a result of pedestrian motion. Three different L1 Doppler estimates obtained from the following methods are shown, namely (a) L1 only processing (that is, only L1 signal.
is used) with traditional atan(cross/dot) FLL discriminator, (b) L1 only processing with PD discriminator, and (c) proposed L1 + L2 CL-EGC with PD discriminator. It is observed that L1 only processing results in large Doppler errors whenever L1 is in a deep fade. Up to a 40 Hz Doppler error is reported and numerous losses of lock are observed in L1 only tracking considering both discriminators. Similar observations hold true for L2 carrier estimation in all PRNs (06, 12, 25, 24). Comparing the cross-dot discriminator and the PD discriminator, the latter is more robust especially during deep fading conditions as ascertained in [23, 24]. However, under nominal fading conditions, the PD discriminator estimation is noisy compared to the cross-dot discriminator, as shown in Figure 9 during a moderate fading window for the same data set. In such cases, a traditional FLL discriminator operating on a single frequency outperforms the proposed method or PD discriminator operating on single frequency.

Figure 10 compares the performance of Discriminator Level (DL) combining with that of the proposed correlator level combining for the same harsh fading window as that of Figure 8. The tracking method based on EGC of cross-dot discriminator outputs performs poorer than their MRC. If the discriminator outputs are combined with equal gain, then the contribution from the corrupted discriminator output (the one from the faded signal) will degrade the contribution from a good signal as well. Hence, MRC based weighting is more suitable in DL combining. Although DL-MRC provides better results than independent tracking, the CL-MRC with PD discriminator produces robust tracking with more accurate estimation. The Root Mean Square Error (RMSE) statistics of L1/L2 carrier and code Doppler estimation obtained from various tracking configurations is discussed later.

The overall Frequency Lock Indicator (FLI) is improved due to combined tracking. The FLI is directly proportional to the estimated Doppler frequency error, $f$. FLI can be written as [28]

$$FLI = \cos(4\pi f T_c) = \frac{\text{dot}^2 - \text{cross}^2}{\text{dot}^2 + \text{cross}^2}$$

The improved accuracy in the estimated parameters (Doppler and code phase) improves the correlation values, which in turn enhance the FLI. In a general L1 receiver, the tracking modes such as wide band FLL, narrow FLL, Assisted DLL, or re-acquisition are dynamically varied based on L1’s FLI. However, during L1 fading, there may be instances where L2’s FLI is better than that of L1.

![Fig. 8 - Estimated L1 carrier Doppler for PRN25 in Pedestrian Data 1 during harsh fading](image1)

![Fig. 9 - Estimated L1 carrier Doppler for PRN25 in Pedestrian Data 1 during moderate fading](image2)

![Fig. 10 - Estimated L1 carrier Doppler for PRN25 in Pedestrian Data 1 during harsh fading](image3)
depending on the strength of two signals. Using only L1’s FLI may cause the receiver to falsely enter re-acquisition mode even if the estimated parameters are relatively accurate due to aiding from L2’s power. To avoid such false alarms, the combined tracking selects the largest FLI among L1 and L2 to switch between the tracking modes.

Figure 11 shows the RMSE of L1 and L2 carrier Doppler estimates for all dual frequency PRNs in Pedestrian Data 1. Five different estimates are shown, namely (a) single frequency processing with cross-dot discriminator, (b) L1 + L2 DL-MRC with cross-dot discriminators, (c) single frequency processing with PD discriminator, (d) proposed L1 + L2 CL-EGC with PD discriminator, and (e) proposed L1 + L2 CL-MRC with PD discriminator. Comparing single frequency cross-dot and PD discriminator, the former showed better performance for moderately faded PRNs (PRN 06 and PRN 12). PRN 25 and PRN 24 experience deep fading in most sections of the data, therefore the PD discriminator typically produced less estimation error as a result of improved robustness and reduced losses of lock. Nonetheless, in the case of combined tracking, CL combining showed improvements when compared to DL combining. However, occasionally when the signal strength values of both signals drop almost simultaneously, the combined tracking produced poor results without losing lock whereas the single frequency tracking lost lock completely, thus avoiding noisy measurement generation. Nevertheless, overall estimation of the carrier Doppler values is better for the CL combined tracking case as shown in Figure 11. Joint estimation using the combined signal has improved the estimation accuracy and robustness of both L1 and L2 tracking. All PRNs in Pedestrian Data 1 show improvements compared to single frequency tracking due to increased decorrelation between L1 and L2 signals. The L1 carrier error reduction is about 48% for PRN 25, 39% for PRN 12, 38% for PRN 06, and 29% for PRN 24. Similar improvements are observed in the case of L2 tracking as well.

The L1 and L2C power values vary independently in most parts of the residential complex fading environment (Pedestrian Data 2). However, the independent fading is not as much as the one observed under dense foliage. In some sections of this data, both L1 and L2 signals are simultaneously attenuated by surrounding structures. Figure 12 shows the RMSE of L1 and L2 carrier Doppler estimates for all dual frequency PRNs in Pedestrian Data 2. The percentage of L1 carrier Doppler error reduction is 50% for PRN 24, 18% for PRN 12, 37% for PRN 17, and 4% for PRN 06. The latter showed minimal improvement because it was at a high elevation and hence already had good LOS visibility in most sections of the data; thus the diversity combining did not produce significant improvements.

Enhancements are also observed in code Doppler estimation in both data sets. Figure 13 shows the RMSE of code Doppler estimation errors in Pedestrian Data 1 and 2. In Pedestrian Data 1, the

![Fig. 11 - L1 and L2 carrier Doppler RMSE for Pedestrian Data 1; (a) single frequency processing with x-d discriminator, (b) L1 + L2 DL-MRC with x-d discriminators, (c) single frequency processing with PD discriminator, (d) L1 + L2 CL-EGC with PD discriminator and (e) L1 + L2 CL-MRC with PD discriminator. [Color figure can be viewed at wileyonlinelibrary.com and www.ion.org]

![Fig. 12 - L1 and L2 carrier Doppler RMSE for Pedestrian Data 2; (a) single frequency processing with x-d discriminator, (b) L1 + L2 DL-MRC with x-d discriminators, (c) single frequency processing with PD discriminator, (d) L1 + L2 CL-EGC with PD discriminator and (e) L1 + L2 CL-MRC with PD discriminator. [Color figure can be viewed at wileyonlinelibrary.com and www.ion.org]
code Doppler error reduction is 52% for PRN 25, 28% for PRN 12, 36% for PRN 06, and 43% for PRN 24. In Pedestrian Data 2, it is 57% for PRN 17, 10% for PRN 12, 45% for PRN 24, and insignificant change for PRN 06. The DLLs inherently benefit from diversity combining for two reasons: (a) correlator level combining of early and late correlation values from L1 and L2 branches, and (b) carrier-assisted code tracking; since the carrier estimation is enhanced, the carrier-assisted code tracking further improves the code estimation.

### Mean Track Time and Number of Lock Losses

Equally important metrics to evaluate the tracking performance are the MTTL, number of lock losses, and Mean Signal Gap. MTTL is the average time during which the loop sustains lock. The Mean Signal Gap is the time gap observed for the loop to re-enter the tracking state after losing lock. During this time the receiver may be either in re-acquisition mode or in wide band tracking mode trying to maintain lock. All these metrics are evaluated empirically in Table 3, which lists the number of losses of lock, MTTL, and Mean Signal Gap observed in L1 only tracking and L1 + L2 CL combined tracking cases during the observation window of 400 s to 450 s for Pedestrian Data 1 and Pedestrian Data 2. Given its robustness during harsh fading, the PD discriminator is used for analysis in the case of L1 only tracking. In both cases, loss of lock is declared whenever the FLI value drops below 0.2. L1 only tracking reported a number of lock losses in both data sets. Combined tracking did not lose lock in Pedestrian Data 1, while it reported a few losses in Pedestrian Data 2 although lower than the L1 only case. MTTL is significantly lower and the Mean Signal Gap is larger when L1 only is used for tracking. Figure 14 shows the tracking status of the two pedestrian data sets for L1 only tracking and L1 + L2 CL combined tracking cases. Green indicates that tracking is ON (bit synch achieved) and dotted red indicates that tracking is OFF (loss of lock). It clearly shows that the proposed method sustains tracking for a long time as well as re-acquires the signal faster, which means better position solution (continuity as well as availability) can be achieved.

Although correlator level combining may not produce benefits compared to other tracking methods in every epoch under all scenarios, its significance can be observed when the SNR of two individual signals are marginally above the loss of lock threshold. When the signals are combined at the correlator level, the overall SNR of the combined signal will be better than the two, thus leading to continuous tracking.

### Position and Velocity Estimation Performance

In this section, the navigation solution performance of the proposed method against the L1 only case is analyzed. The following applies to both

#### Table 3—MTTL, Mean Signal Gap and number of lock losses

<table>
<thead>
<tr>
<th>Data</th>
<th>PRN</th>
<th>Number of loss of locks</th>
<th>MTTL [s]</th>
<th>Mean Signal Gap [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>L1 only</td>
<td>L1 + L2</td>
<td>L1 only</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>86</td>
</tr>
<tr>
<td>25</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>36</td>
</tr>
<tr>
<td>24</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>3</td>
<td>1</td>
<td>115</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>1</td>
<td>0</td>
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<td>17</td>
<td>9</td>
<td>3</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>24</td>
<td>10</td>
<td>8</td>
<td>0</td>
<td>10</td>
</tr>
</tbody>
</table>

*Lost lock once. Hence, MTTL cannot be averaged. Time of loss of lock is shown.*
the L1 only case and the L1 + L2 CL combined case: (a) Kalman Filter (KF) is used to estimate the 3D position and velocity states, (b) Noisy measurements are rejected based on FLI (<0.4), and (c) Identical system model and process noise values are used in both L1 only and L1 + L2 cases. Process noise values used are as follows: North and East Velocity Spectral Density = 0.25 m/s/s/√Hz and Vertical Velocity Spectral Density = 0.1 m/s/s/√Hz.

Figure 15 shows the position estimation plot for Pedestrian Data 2. The green curve is the true trajectory estimated by SPAN-LCI™ with accuracy better than 1 m. Dotted arrows indicate the first loop, and the solid arrows indicate the second loop. The duration of the two loops is 450 s. Clearly, the L1 only tracking case results in an erroneous trajectory due to several losses of lock and a reduction of available measurements. Because noisy measurements and long signal gaps lead to a reduction in the measurement count, the KF continues to estimate the states relying mostly on the system model, which itself may not be accurately modeled. However, in the case of combined tracking, although the same system model is used, it continues to result in relatively better estimates for two reasons, namely (a) Doppler and code phase estimation accuracy has improved, which in turn improves measurement accuracy; and (b) tracking continuity is better, meaning that measurement availability is better. The L1 + L2 CL combined tracking is tested with two types of combining, namely the EGC and MRC. MRC results in better 2D positions compared to EGC. The errors statistics obtained from these plots will be discussed later.

Figure 16 shows the estimated position plots for Pedestrian Data 1. The green curve is the true
trajectory estimated by SPAN-LCI™. Dotted arrows in the first sub-figure indicate the first loop and solid arrows indicate the second loop. The duration of the two loops is 400 s. The L1 only tracking case results in large position errors due to increased measurement errors and discontinuous measurement availability, as in the previous case. Both the EGC and MRC of the combined tracking case produce better position estimates compared to the single frequency tracking case. Between EGC and MRC, the latter results in improved solutions. Figure 17 shows the 3D position errors for L1 only and combined tracking cases for the dense foliage test.

As discussed earlier, KF continues to provide the position and velocity estimates relying mostly on the system model even if the satellite count (measurements) falls below four. This may not give a clear picture about the discontinuity of the navigation solution. Hence, least squares (LS)-based solutions are obtained for both data sets and compared between L1 only and L1 + L2 CL-MRC cases. Figure 18 shows the number of satellites generating measurements. The total number of PRNs processed in Pedestrian Data 1 was six including single frequency (L1) transmitting satellites PRN 02 and PRN 10 (as of 15 July 2015, the day of the test). In many parts of Pedestrian Data 1, the L1 only case had less than four satellites generating valid measurements. Hence, the LS solution is discontinuous as shown in Figure 19, while the solution from the L1 + L2 tracking case is continuous because the number of satellites generating measurements was always greater than or equal to four. The occasional transition in the number of satellites from six to five in the L1 + L2 tracking case for Data 1 in Figure 18 is due to the loss of lock on either PRN 02 or PRN 10. For Pedestrian Data 2, the total number of PRNs considered is five including PRN 02. In the L1 only case most parts of the data had less than four satellites. Hence, its LS solution is discontinuous as shown in Figure 19. In the combined tracking case, only a few epochs are absent.

Statistics obtained from the navigation domain analysis using KF based estimation are given in Tables 4 and 5 for Pedestrian Data 1 and Pedestrian Data 2, respectively. The Root Mean Square (RMS), mean, and absolute maximum errors of 2D positions, 3D positions, and 3D velocities are shown. The values are computed after the time epoch 50 s (time after which the receiver entered the respective fading environment). The RMSE reduction obtained

![Fig. 16-2D Position plots for Pedestrian Data 1.](wileyonlinelibrary.com and www.ion.org)

![Fig. 17-Position errors for Pedestrian Data 1.](wileyonlinelibrary.com and www.ion.org)
from combined tracking is significant. In Pedestrian Data 1, the 2D and 3D error reductions achieved by MRC are 66% and 52%, respectively. The east velocity error is reduced by 19% and the north velocity by 33%. Similarly, the RMS 2D and 3D error reductions in Pedestrian Data 2 are 62% and 50%, respectively. The east velocity error is reduced by 22% and the north velocity by 32%. In addition, the mean and absolute maximum errors are also greatly reduced by frequency diversity combining. Since

Table 4—Navigation solution error statistics for Pedestrian Data 1

<table>
<thead>
<tr>
<th>Metric</th>
<th>Tracking method</th>
<th>L1 only</th>
<th>L1 + L2</th>
<th>L1 + L2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L1 only</td>
<td>EGC</td>
<td>MRC</td>
<td>MRC</td>
</tr>
<tr>
<td>2D position [m]</td>
<td>rms</td>
<td>7.5</td>
<td>6.0</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>6.5</td>
<td>5.0</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>12.0</td>
<td>14.0</td>
<td>6.0</td>
</tr>
<tr>
<td>3D position [m]</td>
<td>rms</td>
<td>9.5</td>
<td>7.0</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>8.5</td>
<td>6.0</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>14.0</td>
<td>14.0</td>
<td>8.5</td>
</tr>
<tr>
<td>East velocity [m/s]</td>
<td>rms</td>
<td>-0.01</td>
<td>0.01</td>
<td>-0.01</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>0.21</td>
<td>0.20</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>0.83</td>
<td>0.91</td>
<td>0.73</td>
</tr>
<tr>
<td>North velocity [m/s]</td>
<td>rms</td>
<td>0.32</td>
<td>0.28</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>-0.06</td>
<td>-0.06</td>
<td>-0.03</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>1.78</td>
<td>1.27</td>
<td>1.20</td>
</tr>
<tr>
<td>Up velocity [m/s]</td>
<td>rms</td>
<td>0.14</td>
<td>0.14</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>0.47</td>
<td>0.45</td>
<td>0.47</td>
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Table 5—Navigation solution error statistics for Pedestrian Data 2

<table>
<thead>
<tr>
<th>Metric</th>
<th>Tracking method</th>
<th>L1 only</th>
<th>L1 + L2</th>
<th>L1 + L2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L1 only</td>
<td>EGC</td>
<td>MRC</td>
<td>MRC</td>
</tr>
<tr>
<td>2D position [m]</td>
<td>rms</td>
<td>12.0</td>
<td>5.0</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>8.0</td>
<td>4.0</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>25.5</td>
<td>16.0</td>
<td>11.5</td>
</tr>
<tr>
<td>3D position [m]</td>
<td>rms</td>
<td>13.0</td>
<td>8.5</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>10.0</td>
<td>7.5</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>25.5</td>
<td>17.0</td>
<td>12.0</td>
</tr>
<tr>
<td>East velocity [m/s]</td>
<td>rms</td>
<td>0.22</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>0.02</td>
<td>-0.01</td>
<td>-0.01</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>1.11</td>
<td>0.73</td>
<td>0.88</td>
</tr>
<tr>
<td>North velocity [m/s]</td>
<td>rms</td>
<td>0.34</td>
<td>0.25</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>-0.04</td>
<td>-0.02</td>
<td>-0.03</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>1.91</td>
<td>1.11</td>
<td>0.94</td>
</tr>
<tr>
<td>Up velocity [m/s]</td>
<td>rms</td>
<td>0.18</td>
<td>0.17</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>0.04</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>0.55</td>
<td>0.42</td>
<td>0.60</td>
</tr>
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</table>
there was no deliberate upward motion induced during the data collection, the up velocity error statistics remain almost the same for the single frequency and combined tracking cases. Between EGC and MRC, the latter showed a 35% improvement in 3D position estimation in Pedestrian Data 1 and 23% in Pedestrian Data 2.

CONCLUSIONS

The frequency diversity characteristics of GNSS fading channels using L1 C/A and L2C signals were investigated. The independent fluctuation in $\text{C/N}_0$ values of two signals is the evidence for frequency diversity behavior which was further evaluated by means of complex correlation coefficient, AFC, and LCR values. A new tracking approach utilizing frequency diversity combining directly at the correlator level was implemented and investigated along with its navigation domain performance. The performance of the proposed method was compared to dual-frequency combining at the discriminator level in which the results under pedestrian dynamics in two different harsh fading conditions showed that the former method provides better signal tracking performance. The proposed combined tracking was achieved by EGC and MRC at the correlator level followed by power based carrier and code discriminators to jointly track the two signals. The presented method was also tested against a traditional cross-dot product discriminator operating on single frequency mode. Under moderate fading conditions, the traditional cross-dot product discriminator outperformed the proposed method. Nonetheless, overall performance of correlator-level combined tracking was observed to be better compared to discriminator level combined tracking or the single frequency (L1) tracking under harsh fading scenarios. Therefore, the improved performance is linked to the way in which the two signals are combined, that is, the correlator level combining. The level of improvement from the proposed method depends on the environment and the receiver-reflector geometry. Under dense foliage conditions, the RMSE reduction is in the range of 29% to 48% for the given data sets. Also, correlator level combined tracking sustains the tracking process longer than single frequency tracking. In addition, the navigation domain analysis showed that position and velocity solutions obtained by combined tracking are significantly better. The 3D RMS position errors are reduced by 52% in dense foliage conditions and by 50% in a residential complex environment. Over all, the navigation solution continuity and availability were considerably improved with the proposed method compared to single frequency tracking in harsh fading environments.

REFERENCES


