Complexity and Limitations of GNSS Signal Reception in Highly Obstructed Enviroments

Arif Hussain
Department of Electrical Engineering
Sukkur IBA University
Sukkur, Pakistan
arif.hussain@iba-suk.edu.pk

Faheem Akhtar
Department of Computer Science
Sukkur IBA University
Sukkur, Pakistan
fahim.akhtar@iba-suk.edu.pk

Zahid Hussain Khand
Department of Computer Science
Sukkur IBA University
Sukkur, Pakistan
zahid@iba-suk.edu.pk

Asif Rajput
Department of Computer Science
Sukkur IBA University
Sukkur, Pakistan
asif.ali@iba-suk.edu.pk

Zeeshan Shaukat
Faculty of Information Technology
Beijing University of Technology
Beijing, China
wakeupzee@yahoo.com

Abstract-Multipath (MP) and/or Non Line-Of-Sight (NLOS) reception remains a potential vulnerability to satellite-based positioning and navigation systems in high multipath environments, such as an urban canyon. In such an environment, satellite signals are reflected, scattered or faded, and sometimes completely blocked by roofs and walls of high-rise buildings, fly-over bridges, complex road structures, etc. making positioning and navigation information inaccurate, unreliable, and largely unavailable. The magnitude of the positioning error depends on the satellite visibility, geometric distribution of satellites in the sky, and received signal quality and characteristics. The quality of the received signal (i.e. its statistical characteristics) can significantly vary in different environments and these variations can reflect in signal strength or power, range measurements (i.e. path delay and phase difference), and frequency, all of which distort the correlation curve between the received signal and receiver-generated replicas, resulting in range errors of tens of meters. Therefore, in order to meet stringent requirements defined for the Standard Positioning Service (SPS), the characterization of distortions that could significantly affect a Global Navigation Satellite System (GNSS) signal is essentially important. The scope of this paper is to detect possible imperfections/deviations in the GNSS signal characteristics that can occur due to MP or NLOS reception and analyze its effects. For this purpose, analysis of fading patterns in received signal strength (i.e. Carrier-to-Noise Ratio and strength fluctuations) is carried out in both clear LOS and high MP environment and then its impact on satellite lock state (i.e. tracking) is assessed. Furthermore, phase fluctuations and range residuals are computed to analyze the effects of path delays. The results show that significant variations can occur in GNSS signal characteristics in the MP environment that may result in loss of lock event and inaccurate/faulty range measurements.

Keywords-blockage; availability; continuity; NLOS; accuracy

I. INTRODUCTION

Satellite-based navigation systems (i.e. GNSS/GPS) are providing accurate and reliable Positioning, Navigation, and Timing (PNT) services to hundreds of civilian and military applications across the globe. Some of these include road, rail, and aerial transport, precision agriculture, electric power grids, stock exchange systems, autonomous navigation, Intelligent Transportation Systems (ITS), etc. [1, 2]. Although GNSS is now widely used and providing PNT services with an acceptable level of accuracy in clear open-sky views, the precise positioning and navigation is quite a challenging task in urban canyons. In such an environment, the satellite signals are reflected, scattered, fluctuated (i.e. amplitude and phase) and sometimes completely blocked by roofs and walls of high-rise buildings, fly-over bridges and complex road scenarios, making positioning information inaccurate, unreliable and largely unavailable [3]. Specifically, obstructions in urban canyons can affect the availability and accuracy of GNSS based positioning and navigation services in two ways. At first, they can completely block signals from Line-of-Sight (LOS) satellites resulting in a reduced number of visible satellites. Secondly, they can give rise to a phenomenon commonly known as Multipath (MP) that results in biased range measurements. MP refers to the combination of LOS and a number of NLOS signal

components reflected off nearby obstacles one or more times before reaching the receiver [2]. The MP effects when severe, can significantly affect the quality of the received signal (i.e. statistical characteristics) and thus result in poor positioning performance of the GNSS receiver. In order to ensure that a receiver in a field has achieved the Required Navigation Performance (RNP) threshold, precise analysis of signal characteristics and noise residuals is essentially important [4] and MP/NLOS detection and error analysis under realistic conditions is often a necessary part of the receiver's performance assessment.

The main contribution of this paper is the analysis of the performance of commercial grade GNSS receivers in urban canyons by detecting the possible anomalies in the GNSS signal reception and analyzing its impact. For this purpose, carefully planned field experiments were conducted on pre-surveyed candidates to acquire the actual GNSS data. For a comprehensive analysis of multipath/NLOS effects, five fundamental GNSS signal parameters were investigated and compared. These parameters include Carrier-to-Noise Ratio (CNR) and its variations, satellite lock time, phase fluctuations, and range residuals. Furthermore, the fading patterns in CNR are analyzed in MP/NLOS conditions and their impact on satellite lock state (i.e. tracking) is assessed.

II. GNSS FUNDAMENTALS AND OBSERVATION MODEL

The positioning and navigation problem considered in GNSS is based on estimating the position of a receiver from signals sent by several satellites containing positioning and timing information. More precisely, by measuring the signal propagation time between a specific satellite and the ground receiver, the receiver is able to compute the distance or geometric range. GNSS signals have very low power, and hence they are prone to several errors and biases. The geometric range measured by the receiver is contaminated by these errors or biases, which is why it is called the pseudorange [5, 6]. The general pseudorange observation [7] equation is given as:

$$\rho = \left\| P^k - P_u \right\|_2 + c(dT_u - dT^k) + T^k + I^k + \xi_{MP} + \eta \quad (1)$$

where, ρ represents the pseuodrange between the kth satellite and the receiver (u), $P^m = (x^k, y^k, z^k)^T$ is the satellite position available in navigation messages, $P_u = (x_u, y_u, z_u)^T$ represents the receiver position to be estimated, $\left\| P^k - P_u \right\|_2 = \sqrt{(x^k - x_u)^2 + (y^k - y_u)^2 + (z^k - z_u)^2}$ is the true distance or actual geometric range between the satellite and the receiver, T^k and I^k are the troposheric delay and ionospheric delay respectively, $c(dT_u - dT^k)$ is the error due to clock biases whereas T_u is the receiver's clock bias, T^k is the satellite's clock bias, c represents the speed of light, ξ_{MP} is the error factor due to MP/NLOS reception, and η represents the receiver or measurement noise.

III. METHODOLOGY

In an urban area, GNSS signals may arrive at the receiver not only through the direct (LOS) path, but also through several indirect paths due to the presence of different obstructions (high rise buildings, trees, bridges, etc.) in the way of the

signal. The superposition of direct LOS and one or more indirect signals yields a compound signal (i.e. MP signal) [7]. The MP/NLOS can affect the quality of the navigation signal in a number of ways, e.g. it can introduce random fluctuations in amplitude and phase of the received signal or it can result in biased range measurements. In this research, the detailed analysis of MP/NLOS effects is carried out by investigating and comparing the five fundamental parameters of the GNSS signal. These parameters include CNR, variations in CNR, satellite lock time, phase fluctuations, and range residuals as shown in Figure 1. Generally, the MP signal [8, 9] can be modeled as:

$$S_{MP} = A_d \times \cos(\emptyset) + A_r \times \cos(\emptyset + \Delta\emptyset) \quad (2)$$

where A_d and A_r indicate the amplitudes of direct (LOS) and reflected (NLOS) signals respectively, $\emptyset$ denotes the phase and $\Delta\emptyset$ denotes the phase shift in the NLOS signal [10, 11]. The amplitude composite signal (S_{MP}) and phase shift can be estimated as:

$$A_m = \sqrt{A_d^2 + A_r^2 + 2A_d^2 A_r^2 cos\Delta\emptyset} \quad (3)$$

$$\Delta\emptyset_m = arctan\left(\frac{A_r sin\Delta\emptyset}{A_d + A_r cos\Delta\emptyset}\right) \quad (4)$$

where $\Delta\emptyset_m$ and A_m denote the phase shift and amplitude influence by the multipath (i.e. the composite signal).
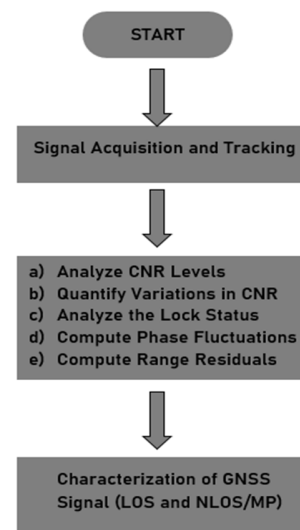

Fig. 1.   Navigation signal analysis methodology.

A. Carrier-to-Noise Ratio

CNR is the fundamental quality indication factor of any RF (i.e. GNSS) signal and it represents the strength/power of the received signal. In GNSS, the quality of the signal is directly linked with positioning and navigation accuracy. Strong CNR values with minimal fluctuations result in better positioning performance [12, 13]. However in urban canyons, the CNR tends to be lower and fluctuates around the nominal asynchronously due to superposition of direct LOS and one or more NLOS signals. The CNR can be estimated as:

$$CNR = A_d^2 + A_r^2 + A_\xi^2 + 2A_d^2 A_r^2 A_\xi^2 cos\Delta\emptyset \quad (5)$$

It is obvious that CNR can be significantly influenced by MP effects. The multipath can either be destructive or constructive depending upon the phase shifts.

B. Variations Patterns in CNR

As discussed above, in MP environment, the CNR may fluctuate asynchronously around the nominal. These fluctuations and their impact depend upon the severity of the MP effect. The variations in CNR can be estimated as:

$$\Delta CNR = \frac{10\times(CNR_{max})-10\times(CNR_{min})}{10\times(CNR_{max})+10\times(CNR_{min})} \quad (6)$$

where CNR_{max} and CNR_{min} are the maximum and minimum CNR values of the received signal respectively.

C. Satellite Lock State

In a GNSS receiver, the signals are initially acquired, tracked and then a navigation message is decoded to estimate the positioning solution. During the tracking stage, the receiver keeps track of the acquired satellite and maintains it in lock state. The MP/NLOS reception can interrupt the signal tracking due to the degraded signal quality and may result in the loss of lock events. The loss of lock interrupts the connection between the satellite and the receiver leading to non-visibility of the satellite even if the satellite is present at the particular time and place. The duration and occurrence of loss of lock events depends upon the strength of the signals. Lower CNR values and/or significant CNR variations may result in frequent loss of locks.

D. Phase Deviations

According to (4), MP signal can introduce phase shifts in the received signal which ultimately contaminates the range measurements. These shifts/variations in phase can be quantified by computing the standard deviation of phase over a certain interval (60s). In MP free environment, these variations are observed to be negligible.

E. Range Residuals

Pseudorange represents the distance between the satellite and the ground receiver, measured by the estimation of the propagation time of the satellite signal. The propagation time can be affected by several factors like the ionospheric delay, the tropospheric delay, clock biases, and longer travel time due to MP/NLOS resulting in extended pseudorange and thus inaccurate and unreliable positioning solution. MP/NLOS remains an unmodeled and major source of error due to its nondeterministic nature, while other effects can be compensated or modeled. The MP error in the pseudorange can be quantified by range residuals. The range residuals are simply the change in pseudorange from one epoch to the next. In case of a static receiver, the range residuals remain almost zero for direct LOS signals, however this may not be the case in MP environment [14].

IV. FIELD EXPERIMENTS AND DATA COLLECTION

In order to precisely investigate the complexity and limitation of GNSS signal reception in real time, a carefully planned field experiment is conducted on a pre-surveyed candidate site to acquire and record (log) the GNSS signals. The field experiment was performed in the Sukkur IBA University, Pakistan. The site, as shown in Figure 2, has a high degree of realism, being surrounded by buildings and dense tress. In such an environment, there are significant chances of MP and NLOS receptions that can degrade the positioning and navigation accuracy.
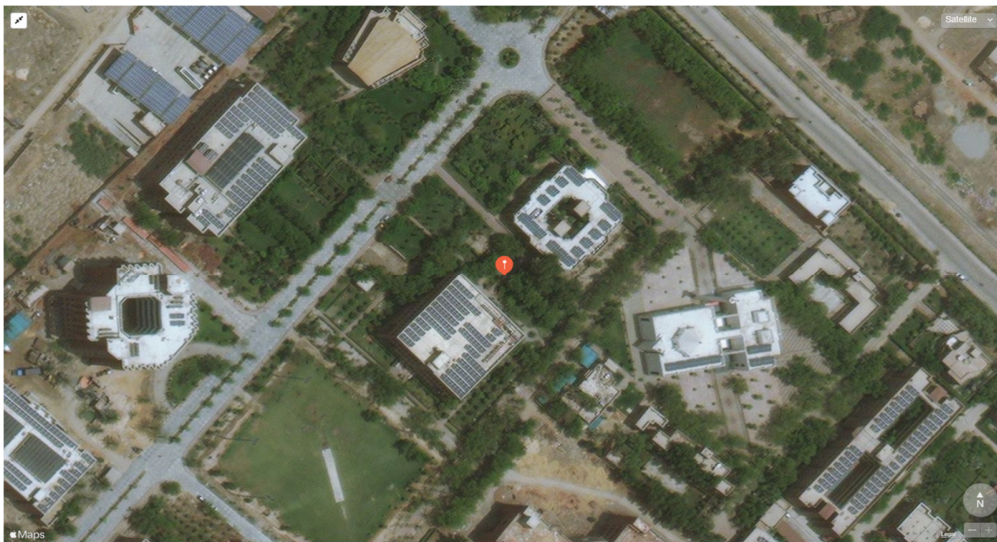

Fig. 2.   Experimental site for GNSS raw data/signal acquisition (Google maps, © CNES / Airbus, Maxar Technologies)..

During the field experiment, real time GNSS signals/data were logged by a Septentrio Polarx5S receiver connected to a PolaNt Choke Ring B3/E6 Antenna and the post processing was done in Matlab. The setup is shown in Figure 3. The Septentrio Polarx5S GNSS receiver is multi–frequency, multi–constellation, capable of receiving 544 hardware channels to

instantaneous track all satellites signals and can log data at 50Hz. The Septentrio receiver locked the GPS (L1C/A, L1P, L2P, L2C, L5), GLONASS (L1, L2, L3) GALILEO (E1, E5ab, AltBoc, E6), BEIDOU (B1, B2, B3), SBAS (L1, L5), QZSS (L1, L2, L5) signals [15]. The letters show the frequency bands related to each particular GNSS system. It has the capability of logging real time GNSS data for all frequencies. The PolaNt Choke Ring antenna is a high precision wideband antenna that is compatible with the PolaRx group and has the capability of receiving all GNSS signals [16].

Fig. 3.   Experimental setup for capturing GNSS data.

V.   RESULTS AND DISCUSSION

The precise positioning and navigation is highly dependent on the quality/characteristics of the GNSS signal. The comprehensive analysis of GNSS signal characteristics in NLOS or Multipath environment is presented in Figures 4 and 5. This study is performed on actual GNSS data acquired in MP environment in static mode and it is focused on identifying/showing the signal parameters affected by MP/NLOS reception. Figure 4 shows the fundamental signal characteristics (CNR, CNR variations in relationship with elevation angle and lock time) of one satellite PRN 12 for an observation period of 5 hours (from 05:30 to 10:30 UTC). Based on the signal characteristics, the observation period is categorized into two segments: MP/NLOS and LOS. Figure 4(a) shows the CNR of the L1 and L2 signals. It is obvious that CNR is significantly influenced by the MP effect. Under MP conditions, the acquired CNR is much lower (it drops to 30dB) and significantly fluctuates between 30 and 40dB even at good elevation angles ($\theta \geq 20$). Furthermore, the receiver is not able to acquire/track when the CNR drops below 30dB. For better analysis of the severity of the NLOS/MP effects on CNR of the received signal, the variations in the CNR are analyzed and quantified with respect to the elevation angle. Figure 4(b) shows the CNR variations (ΔCNR) in relationship with the elevation angle. Due to the MP/NLOS, significant variations in CNR even at higher elevation angles ($20 \leq \theta \leq 40$) are observed. The results show that when the ΔCNR is greater than 0.3, there are significant chances of the loss of lock event. This can be seen in Figure 4(c). In GNSS, when a connection between the satellite and the receiver is established (i.e. the satellite is in

tracking) then the satellite is in lock state. Figure 4(c) shows that MP/NLOS can interrupt the lock state of the satellite. It can be clearly seen that the lock state of the satellite is frequently interrupted when CNR variations are higher. Frequent loss of locks may affect the continuity of GNSS service and overburden the processing load because the receiver has to reinitiate the acquisition process.
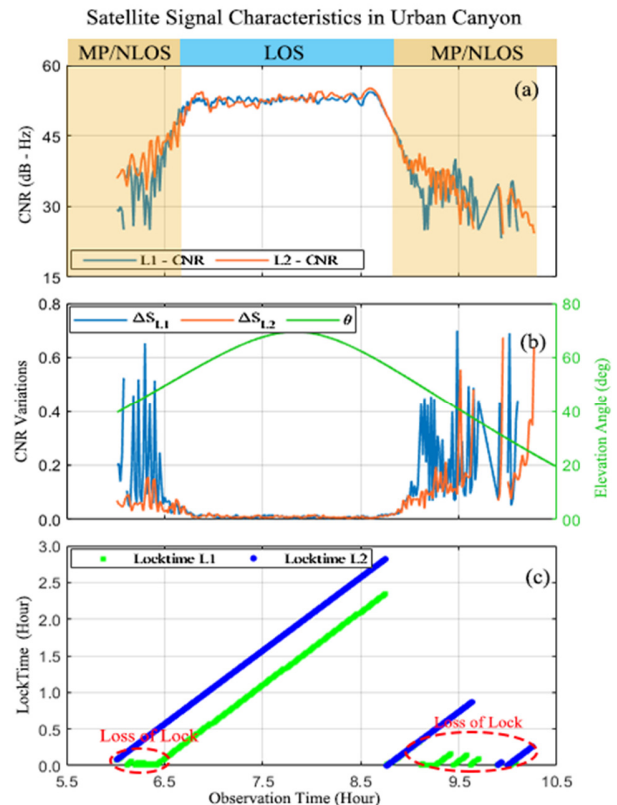

Fig. 4.   Satellite signal characteristics in urban canyon.

Multipath (MP) signals are reflected by obstacles one or more times before reaching the GNSS antenna. Since we are estimating distances to the satellites, and that is the foundation of the positions in GNSS, a signal that bounces from an obstruction before it reaches the GNSS antenna causes a problem. If there is a bend in the signal, it will affect the range measurement. These effects can be analyzed by observing phase fluctuations/deviations and computing range residuals. Figure 5 shows the range characteristics (phase deviations and range residuals) of the same satellite, and for the same observation period. It can be observed that MP/NLOS obviously affects both parameters which are highly correlated with the signal characteristics presented in Figure 4. When the MP effect is significant, it may cause rapid fluctuations in phase and/or results in large range residuals. The results show that during the window from 09:00 to 10:00, phase deviations up to 0.3 were observed along with range residual jumps to 20m. This may result in large positioning error.
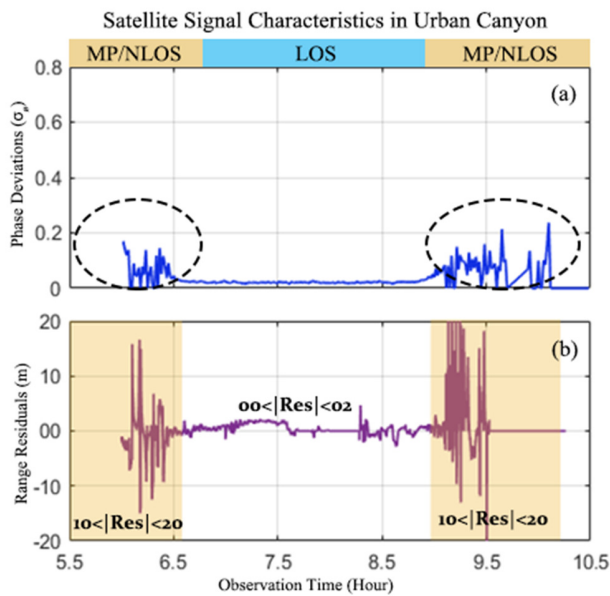
Fig. 5.   Satellite range characteristics in urban canyon.

VI.   CONCLUSION

In this paper, the characteristics of GNSS signal in both LOS and NLOS conditions were investigated and compared. This study is focused in detecting possible imperfections/ deviations in the GNSS signal characteristics that can occur due to MP or NLOS reception only and analyze their effects. Based on the comprehensive analysis of the fundamental characteristics of the signal, it is established that MP/NLOS reception can significantly affect the quality of the received signal. The severe MP effects can result in frequent loss of locks and range errors of more than 10m. Furthermore, the statistical characteristics of direct LOS signal significantly differ from the indirect NLOS signal's.

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