Intermediate Frequency Level GPS Multipath/NLOS Simulator based on Vector Tracking and Ray Tracing

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BIOGRAPHY

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ABSTRACT

Recent years have witnessed a great advancement of urban global positioning system (GPS) positioning performance. In specific, a lot of efforts have been put on the issue of multipath and/or non-line-of-sight (NLOS) signals. Therefore, there's an increasing demand of ground truth of the multipath/NLOS signals for better assessment of the algorithm that mitigates or reduces the multipath/NLOS effects. This paper proposes a novel intermediate frequency (IF) level GPS multipath simulator based on vector tracking and ray tracing techniques. Unlike existing multipath simulators that generates signals from scratch, the proposed simulator generates multipath/NLOS signals in urban canyon based on the IF data that collected in an open-sky area. The parameter conversion of signal parameters like code delay, carrier phase and frequency, etc., is, therefore, the most innovative part of the simulator. To enhance the parameter estimation for the open-sky IF data, the advanced tracking, i.e., vector tracking, is employed for processing. Ray tracing technique is also used to obtain the additional code delay, incident angle, and the frequency change of the reflected signal. An experiment was conducted in Hong Kong. The results show that the proposed simulator can generate multipath/NLOS signals with controllable parameters.

INTRODUCTION

Multipath and non-line-of-sight (NLOS) signals still take on a prominent position on global positioning system (GPS) performance degradation in urban environments. One of the challenges in developing new algorithm for multipath/NLOS mitigation is the lack of the ground truth of the multipath/NLOS signals. This paper proposes a novel GPS multipath/NLOS simulator, aiming at providing researchers and engineers a low-cost simulator that generates controllable and repeatable urban GPS signals with high fidelity.

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There have been many advances in developing multipath simulators, among which we can identify three main types according to the simulators' output. The first type of multipath simulator directly generates multipath-contaminated measurements such as carrier-to-noise ratio (CNR), code and carrier pseudorange measurements, Doppler frequency, etc. The second one operates on the output of correlators or discriminators in the receiver, and the third one outputs raw radio frequency (RF) analog signal or intermediate frequency (IF) digital sequences in the time domain that contain multipath signals. The first type of multipath simulator is highly relied on the model of GPS receivers, especially its antenna characteristic such as gain pattern and polarization efficiency. In addition, the multipath-induced measurement error relies upon the signal processing scheme within a receiver; different signal tracking algorithm parameters (such as spacing, gain and bandwidth) have different multipath suppression capability, which is also the problem of correlator- and discriminator-based methods. The advantage of the former two types of simulator is that it requires no large memory space for storing raw GPS data, which is exactly the disadvantage of the latter type of simulator. However, the third one has the flexibility that it provides researchers and engineers with an opportunity of developing anti-multipath techniques at the baseband signal processing level, and it is independent to the receiver design.

This paper focus on the third type of multipath simulator as mentioned above. A classic example is the MUSTARD (MUltipath Simulator Taking into Account Reflection and Diffraction), which was developed at the Jet Propulsion Laboratory (JPL) [1]. As suggested by its name, this simulator considers the reflection and diffraction from surfaces, edges, and corners via a ray-tracing technique [2]. Another example is the SNACS (Satellite Navigation Radio Channel Signal Simulator) developed at the German Aerospace Center (DLR) in 2009 [3]. The SNACS considers the impact of time-variant multipath channel on GNSS signal transmission. More recently, a commercial multipath simulator, SimGEN®+SE-NAV, by the Spirent Communication, was developed to simulate realistically the GNSS multipath signal in different environments [4]. Like MUSTARD, this product also employs the ray-tracing technique to find all possible paths from the observer to the source of the signal considering a limited number of interactions per emitted rays.

This paper also simulates multipath/NLOS signal at the baseband level mainly based on ray-tracing technique. The core idea behind is that multipath signal is generated based on real IF signal collected in open-sky areas. Parameters like the reflection attenuation, the additional code delay, carrier frequency and phase, etc., are also considered by means of the ray-tracing technique. To enhance the estimation of signal parameters, e.g., code delay, phase, Doppler frequency, etc., the technique of vector tracking loop is used. Compared to existing simulators, the new features of the proposed simulator are twofold. On one hand, the proposed method has no need to generate pseudo-random noise (PRN) code sequence, carrier, and the navigation bit streams due to the utilization of raw open-sky IF signal. On the other hand, to simulate multipath signal with high fidelity, in addition to the consideration of signal attenuation, the change of Doppler frequency, code phase and carrier phase, etc., the advanced vector tracking loop technique is also used to enhance the accuracy of signal parameters estimation.

Multipath/NLOS simulation in urban areas in Hong Kong was carried out. Metrics such as CNR, pseudorange and the positioning result were used to evaluate the performance of the proposed simulator. Results indicate that the proposed simulator can generate realistic multipath signal in urban areas.

In the following sections, the overview of the proposed simulator is first introduced, followed by the core innovative part of the paper, i.e., signal parameter conversion. Next, experimental results conducted will be given. Finally, conclusions are drawn for the paper, and future works are also suggested.

OVERVIEW OF THE PROPOSED SIMULATOR

The illustration of the proposed intermediate frequency level simulator is shown in Fig. 1. Main steps of the algorithm are as follows:

- Step 1: Collect real GPS IF signal in an open-sky area (referred as Point A).
- Step 2: Process the IF signal collected using vector tracking loop-based software receiver [5], and extract signal parameters like signal amplitude, code delay, Doppler, carrier phase, etc., using the direct signal cancellation method [6].
- Step 3: Implement the ray-tracing algorithm at the selected location in urban area (referred as Point B). The outputs in this step include the incident angle, the additional code delay and the change of Doppler and phase of the reflected signal.
- Step 4: Amend the signal parameters obtained in Step 2 according to ray-tracing results in Step 3 to reconstruct the signal that should be received at Point B, including the potential multipath/NLOS signal. In this step, the conversion of signal parameters from Point A to Point B is the core and innovative part of this proposed simulator. To do this, signals (including

the multipath and NLOS signals) are carefully modelled at the baseband level. It is worth noting that dynamic multipath signals can also be simulated based on the static open-sky IF data with the proposed parameter conversion technique. The signal parameter conversion is presented in the following section.

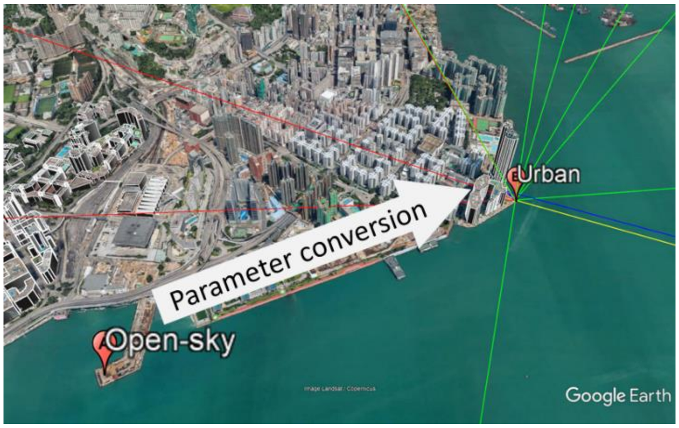


Fig. 1. Illustration of the proposed intermediate frequency level multipath/NLOS simulator.

SIGNAL PARAMETER CONVERSION

This section describes the signal parameter conversion from the open-sky area to the urban canyon. To this end, signal models for LOS/multipath/NLOS are given first, based on which changes of parameters like code delay, carrier frequency and phase, etc., are calculated.

Signal model

In this paper, we simulate the GPS L1 C/A signal. The proposed method can also be applied to other constellations and frequencies with proper modifications. The IF GPS signal for LOS, MP, and NLOS reception, denoted as y^{LOS}, y^{MP}, and y^{NLOS}, respectively, at the output of the RF front-end for one satellite can be expressed as [7]:

$$y^{\mathrm{LOS}}(nT_s) = A \cdot C(nT_s - \tau_0) \cdot D(nT_s - \tau_0) \cdot \cos\left(2\pi (f_{IF} + f_D) nT_s + \varphi_0\right) + \eta(nT_s) \tag{1}$$

$$\begin{aligned} y^{\mathrm{MP}}(nT_s) = {} & A \cdot C(nT_s - \tau_0) \cdot D(nT_s - \tau_0) \cdot \cos\left(2\pi (f_{IF} + f_D) nT_s + \varphi_0\right) \\ & + \alpha^{\mathrm{MP}} \cdot A \cdot C\left(nT_s - \tau_0 - \Delta\tau^{\mathrm{MP}}\right) \cdot D\left(nT_s - \tau_0 - \Delta\tau^{\mathrm{MP}}\right) \cdot \cos\left(2\pi (f_{IF} + f_D) nT_s + \varphi_0 + \Delta\varphi^{\mathrm{MP}} + 2\pi \Delta f_D^{\mathrm{MP}} nT_s\right) \\ & + \eta(nT_s) \end{aligned} \tag{2}$$

$$\begin{aligned} y^{\mathrm{NLOS}}(nT_s) = {} & \alpha^{\mathrm{NLOS}} \cdot A \cdot C\left(nT_s - \tau_0 - \Delta\tau^{\mathrm{NLOS}}\right) \cdot D\left(nT_s - \tau_0 - \Delta\tau^{\mathrm{NLOS}}\right) \cdot \cos\left(2\pi (f_{IF} + f_D) nT_s + \varphi_0 + \Delta\varphi^{\mathrm{NLOS}} + 2\pi \Delta f_D^{\mathrm{NLOS}} nT_s\right) \\ & + \eta(nT_s) \end{aligned} \tag{3}$$

where n is the index of a discrete-time sequence obtained by sampling a continuous-time signal at a sampling rate $f_s = 1/T_s$ with T_s being the sampling interval; A is the amplitude of the direct LOS signal; $C(\cdot)$ the pseudo-random noise (PRN) code; $D(\cdot)$ is the navigation data bit stream; f_{IF} and f_D are the nominal IF frequency and Doppler shift, respectively; α^{MP} and α^{NLOS}, also termed as damping factor, are ratios of the signal amplitude between the multipath/NLOS signal and the direct signal; τ_0 is the code delay of the LOS signal, while $\Delta\tau^{\mathrm{MP}}$ and $\Delta\tau^{\mathrm{NLOS}}$ denote the additional code delay of the reflected signal with respective to the direct signal;

φ_0 denotes the initial carrier phase of the direct signal; $\Delta\varphi^{\mathrm{MP}}$ and $\Delta\varphi^{\mathrm{NLOS}}$ represent the phase change of MP and NLOS relative to the direct signal, respectively; Δf_D denotes the Doppler difference between the direct and the reflected signal; $\eta(nT_s)$ is assumed to be a band-limited additive white gaussian noise.

Parameter conversion

Signal parameter conversion from the open-sky area to the urban canyon can be divided into two parts; one is the LOS to LOS signal conversion, whereas the other is the LOS to MP/NLOS conversion, as illustrated in Fig. 2, where L denotes the path length of the signal.

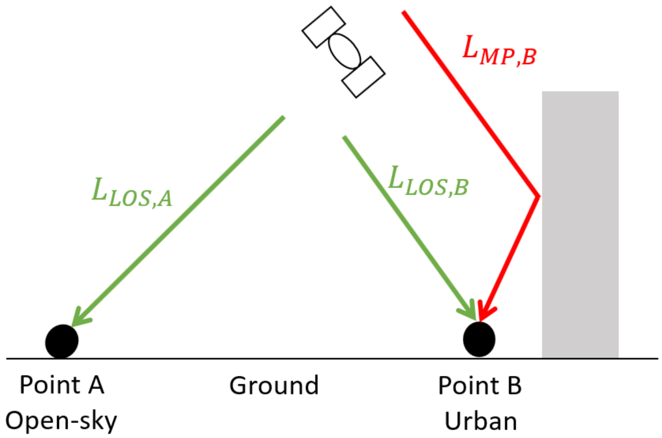


Fig. 2. Signal parameter conversion from the open sky to urban canyon.

A. LOS to LOS conversion

For satellites that are LOS at both Points A and B, the IF signal at Point B can be written as:

$$y_B^{\mathrm{LOS}}(nT_s) = A\cdot C(nT_s-\tau_0-\Delta\tau)\cdot D(nT_s-\tau_0-\Delta\tau)\cdot\cos\left(2\pi\left(f_{IF}+f_D+\Delta f_D\right)nT_s+\varphi_0+\Delta\varphi\right)+\eta(nT_s) \quad (4)$$

where the prefix Δ denotes the difference of the corresponding parameter between A and B, which are calculated as follows:

$$\Delta\tau = \left(L_{LOS,B}-L_{LOS,\mathrm{A}}\right)/\lambda_{CA}+\varphi_\omega \quad (5)$$

$$\Delta\varphi = \left(L_{LOS,B}-L_{LOS,\mathrm{A}}\right)/\lambda_{L1}+\varphi_\omega \quad (6)$$

$$\Delta f_D = \left(\boldsymbol{v}_s\cdot\boldsymbol{h}_A^{\mathrm{LOS}}-\left(\boldsymbol{v}_s-\boldsymbol{v}_{r,B}\right)\cdot\boldsymbol{h}_B^{\mathrm{LOS}}\right)/\lambda_{L1} \quad (7)$$

with $L_{LOS,A}$ and $L_{LOS,B}$ being the length of the direct paths at Points A and B, respectively, λ_{CA} and λ_{L1} the chip length of C/A code and the wavelength of the radio frequency carrier, respectively, and φ_ω the phase wind-up error, which is neglectable [2]. $\boldsymbol{v}_s$ and $\boldsymbol{v}_{r,B}$ are the velocity vectors of the satellite and the receiver at Point B. $\boldsymbol{h}_A^{\mathrm{LOS}} = \left(\boldsymbol{p}_s-\boldsymbol{p}_{r,A}\right)/\left\|\boldsymbol{p}_s-\boldsymbol{p}_{r,A}\right\|$ and $\boldsymbol{h}_B^{\mathrm{LOS}} = \left(\boldsymbol{p}_s-\boldsymbol{p}_{r,B}\right)/\left\|\boldsymbol{p}_s-\boldsymbol{p}_{r,B}\right\|$ are, respectively, the unit vector pointing from the receiver at Points A and B to the satellite with $\boldsymbol{p}$ denoting the position vector.

B. LOS to multipath/NLOS conversion

Both multipath and NLOS signals are due to reflection. For simplicity, we only present the signal parameter conversion from LOS at Point A to multipath at Point B. The multipath signal at Point B is

$$
\begin{aligned}
y_B^{\mathrm{MP}}(nT_s) &= y_B^{\mathrm{LOS}}(nT_s) \\
&+ \alpha^{\mathrm{MP}} \cdot A \cdot C\left(nT_s - \tau_0 - \Delta\tau^{\mathrm{MP}}\right) \cdot D\left(nT_s - \tau_0 - \Delta\tau^{\mathrm{MP}}\right) \cdot \cos\left(2\pi\left(f_{IF} + f_D\right)nT_s + \varphi_0 + \Delta\varphi^{\mathrm{MP}} + 2\pi\Delta f_D^{\mathrm{MP}} nT_s\right) \\
&+ \eta(nT_s)
\end{aligned}
\tag{8}
$$

where the damping factor α^{MP} of the reflected signal can be calculated as [2]

$$\alpha^{\mathrm{MP}} = \rho F \eta_a \tag{9}$$

where ρ is the reflection coefficient; F is the polarization efficiency; and η_a is the user antenna gain ratio between the LOS and reflected signal. The calculation of $\Delta\tau^{\mathrm{MP}}$ and $\Delta\varphi^{\mathrm{MP}}$ is as follows:

$$\Delta\tau^{\mathrm{MP}} = \left(L_{MP,B} - L_{LOS,B}\right) / \lambda_{CA} + \varphi_\omega \tag{10}$$

$$\Delta\varphi^{\mathrm{MP}} = \left(L_{MP,B} - L_{LOS,B}\right) / \lambda_{L1} + \varphi_\omega \tag{11}$$

where $L_{MP,B}$ is the multipath length including the one from the reflecting point to the receiver. The Doppler difference between the multipath signal and the direct signal, Δf_D^{MP} can be calculated as [8]

$$
\begin{aligned}
\Delta f_D^{\mathrm{MP}} &= f_D^{\mathrm{MP}} - f_D^{\mathrm{LOS}} \\
&= \left(\boldsymbol{v}_{r,B} \cdot \boldsymbol{h}_A^{\mathrm{LOS}} - \boldsymbol{v}_{r,B} \cdot \boldsymbol{h}_B^{\mathrm{MP}}\right) / \lambda_{L1}
\end{aligned}
\tag{12}
$$

where $\boldsymbol{h}_B^{\mathrm{MP}} = \left(\boldsymbol{p}_{reflect} - \boldsymbol{p}_{r,B}\right) / \left\| \boldsymbol{p}_{reflect} - \boldsymbol{p}_{r,B} \right\|$ is unit vector pointing from the receiver at Point B to the reflecting point; $\boldsymbol{p}_{reflect}$ denotes the position vector of the reflecting point.

Finally, to calculate the reflection coefficient ρ of the reflected signal, we use the Fresnel model as shown in Fig. 3. It is assumed that each signal is reflected by a mirror-like surface from a single incoming direction to a single outgoing direction. The Fresnel reflection coefficient is a function of the incidence angle θ_i and the relative permittivity of the material $\varepsilon_2/\varepsilon_1$. The Fresnel reflection coefficients can be resolved into perpendicular $\rho_\perp$ and parallel components ρ_{P}, which are calculated as [9]

$$\rho_\perp = \frac{\varepsilon_2/\varepsilon_1 \cdot \cos\theta_i - \sqrt{\varepsilon_2/\varepsilon_1 - \sin^2\theta_i}}{\varepsilon_2/\varepsilon_1 \cdot \cos\theta_i + \sqrt{\varepsilon_2/\varepsilon_1 - \sin^2\theta_i}} \tag{13}$$

$$\rho_{\mathrm{P}} = \frac{\cos\theta_i - \sqrt{\varepsilon_2/\varepsilon_1 - \sin^2\theta_i}}{\cos\theta_i + \sqrt{\varepsilon_2/\varepsilon_1 - \sin^2\theta_i}} \tag{14}$$

The final reflection coefficient ρ is [10]

$$\rho = \frac{1}{2}\left(\rho_\perp - \rho_{\mathrm{P}}\right) \tag{15}$$

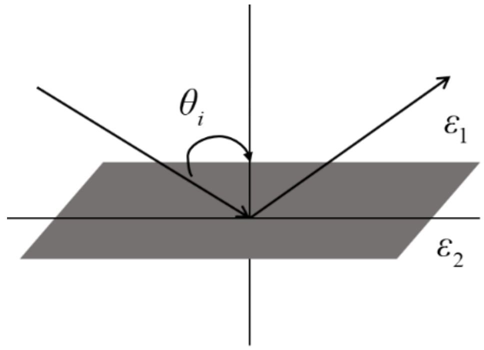


Fig. 3. Fresnel Reflection model [9].

EXPERIMENTAL RESULTS

This section presents the experimental results conducted in Hong Kong as shown in Fig. 4. Point A was at the peak of a hill, where open-sky IF GPS data were collected on Sep. 19, 2019. The Ublox-F9P receiver and the NSL Stereo front-end shared one antenna via a splitter. We use the RTKLIB to process the Ublox-F9P carrier measurements and the fixed (integer-resolved) solution was used as the ground truth of Point A. Point B was selected at the urban canyon near Point A. The goal is to simulate the signal received at Point B, where multipath/NLOS signal probably occur. At Point A, five satellites were tracked successfully using the open-source vector tracking-based SDR developed by the Intelligent Positioning and Navigation Laboratory at the Hong Kong Polytechnique University [5].

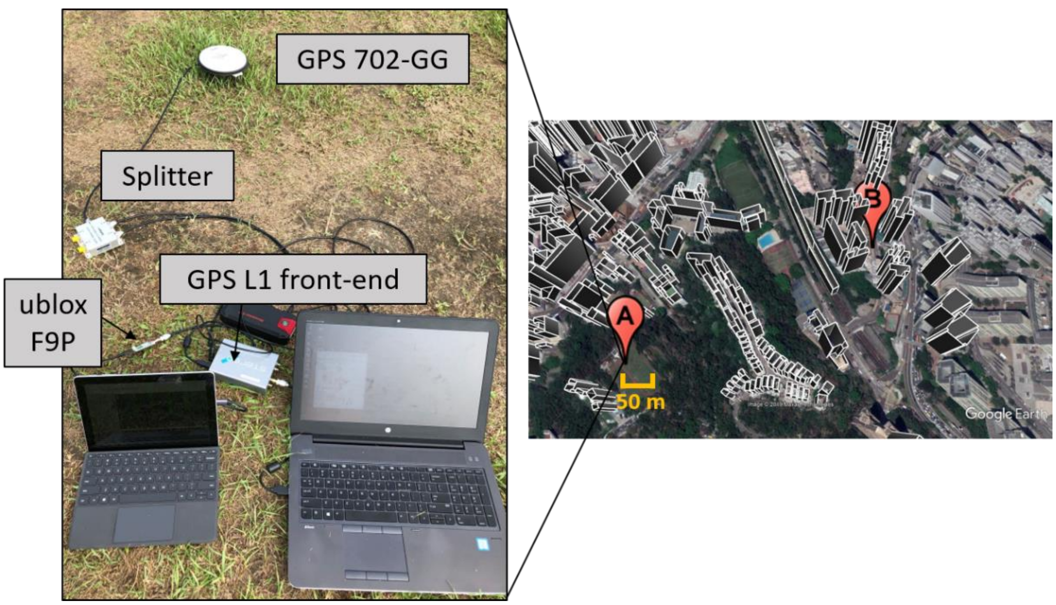
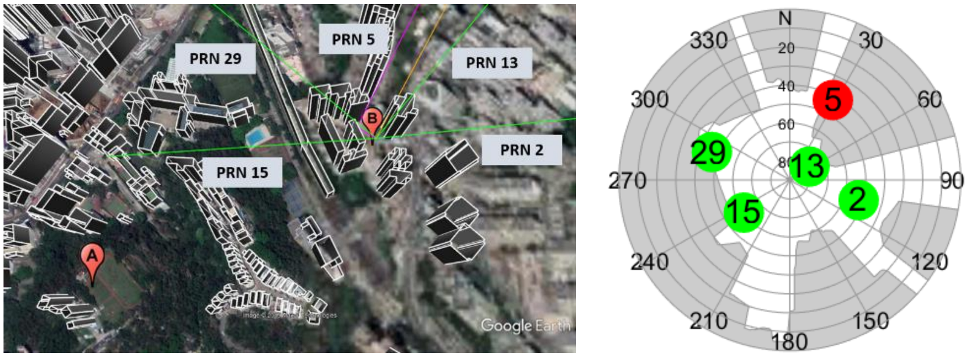


Fig. 4. Experimental scenario and equipment.

Ray tracing results at Point B for satellites tracked at Point A are shown in Fig. 5(a), with the corresponding Skymask shown in Fig. 5(b). It is shown that pseudo-random noise（PRN) 5 was an NLOS satellite; the other four satellites were LOS. We postprocessed about 20-second raw IF data at Point A. To better show the performance of the simulator, we simulated the signal at Point B during the period of 5 to 19 seconds.



(a) (b)

Fig. 5. Ray tracing results at Point B (a), and the Skymask (b).

Fig. 6 shows the additional path delay relative to the LOS signal at Point B and incident angle of the reflected signal for PRN 5 during the simulation period. Based on the ray tracing results, conversions of the signal parameter at Point B were conducted using the method as introduced in previous section. Fig. 7 shows the converted parameter for PRN 5 at Point B. In this paper, we assume that the reflector is flint glass with a relative permittivity of 10 [2]. The polarization efficiency F and the user antenna gain ratio between the LOS and reflected signal η_a are both assumed to be one. Notice that the code delay in Fig. 7 is consisted of two parts: the additional path delay $\Delta\tau^{\mathrm{MP}}$ and the code delay of the non-existent direct path delay at B with respective to that at Point A. The reflection coefficient decides the signal strength. In this case, the decrease of the CNR for the reflected signal should be around $20\log10(0.496) = -6.09$ dB, which is consistent with the result shown in Fig. 8.

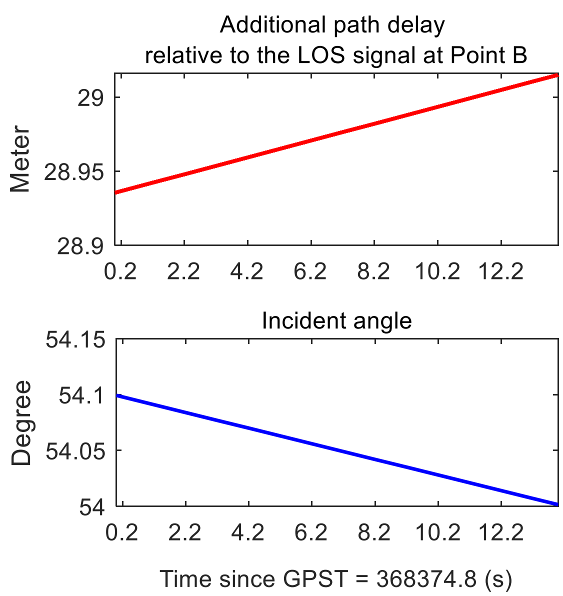


Fig. 6. Additional path delay and incident angle of PRN 5.

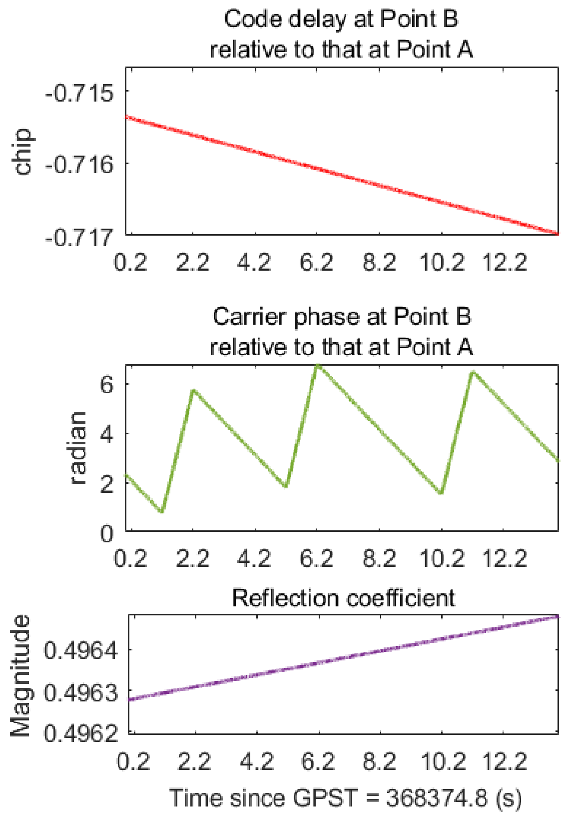


Fig. 7. Converted parameter for PRN 5 at Point B.

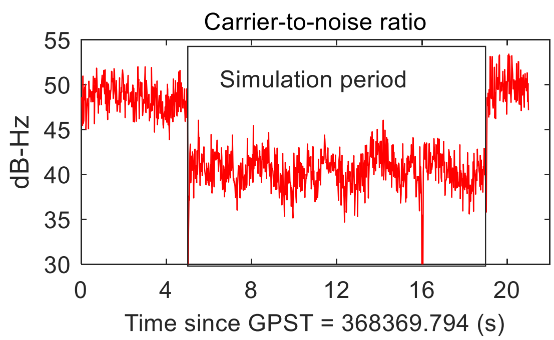


Fig. 8. Carrier-to-noise ratio for PRN 5.

Fig. 9 presents the pseudorange of PRN 5. At Point B, the pseudorange of the direct signal is shorter than that at Point A by around 232 m, i.e., 0.792 chips, at the beginning of the simulation at Point B. It is also shown that the addition path delay of the reflected signal is around 23.1 m, which can be considered consistent with the ray tracing results shown in Fig. 6. Fig. 10 shows the positioning result using the simulated signal at Point B. For comparison, the positioning result without considering the NLOS signal of PRN 5, i.e., using the direct signal of PRN 5 (although it is non-existent), is also shown. It is shown that the positioning result is affected by the consideration of the NLOS signal, which also verifies the effectiveness of the simulator.

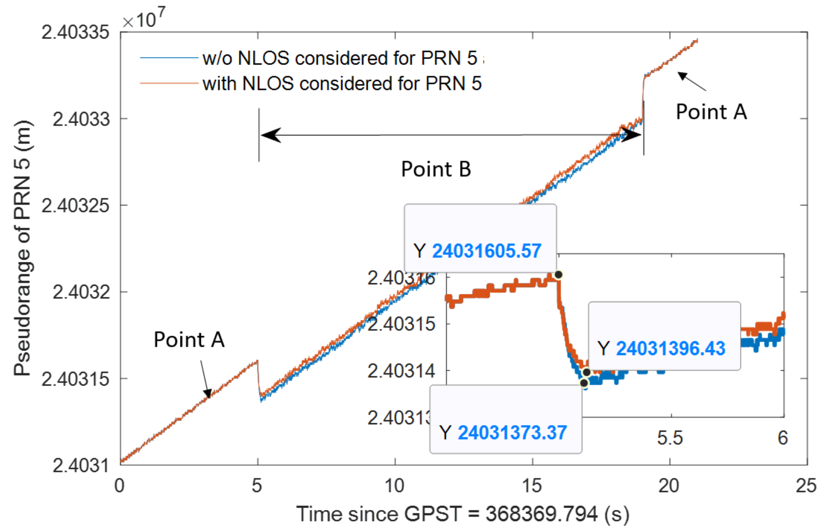


Fig. 9. Pseudorange of PRN 5.

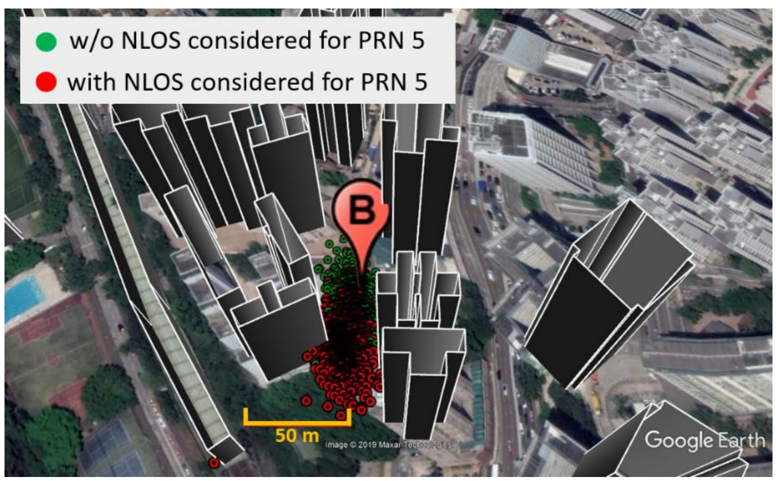


Fig. 10. Positioning result for the simulated signal.

CONCLUSION AND FUTURE WORK

This paper proposes a novel GPS multipath simulator based on vector tracking and ray tracing techniques. The simulator generates multipath/NLOS signals in urban areas based on open-sky IF signal. To this end, the signal parameters at the open-sky area is converted to that in the urban canyon through signal modelling. Ray tracing and vector tracking techniques were used to enhance the signal parameter estimation. Preliminary experimental result indicates the feasibility of the proposed simulator. However, in this paper, we only considered single reflection of the reflected signal and ignored the signal diffraction phenomenon. These issues will be addressed in future works to generate more accurate urban GPS signals. In addition, the proposed simulator can also generate multipath/NLOS signals for dynamic users due to the usage of vector tracking, which controls the signal parameter using user's navigation solution like position and velocity.

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