

GPS Multipath Emulation using Software Generated Signals

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Abstract—Depending on the environment, multipath can be one of the largest error sources contributing to degradation in Global Navigation Satellite System (GNSS) (e.g., GPS) performance. Currently, open-source tools for simulating GPS signals are available and can be used in the testing and evaluation of GPS receiver equipment. These tools can generate GPS signals that, when used by a GPS receiver, result in computation of a position solution that was pre-determined at the time of signal generation. This work utilizes a custom version of the open-source GPS-SDR-SIM to produce emulated multipath GPS signals. A proof of concept was prototyped and demonstrated using this modified version of GPS-SDR-SIM to produce GPS as well as multipath signals. The generated data was processed using a software defined GPS receiver (GNSS-SDR) and it was found that the introduction of simulated multipath signals successfully produced the expected characteristics of a composite multipath signal in simulation.

Keywords—GPS, GNSS, multipath, urban canyon, simulation

I. INTRODUCTION

For commercial air transportation, Positioning, Navigation, and Timing (PNT) data of sufficient quality is, or can be, available during all phases of flight. This data is supplied, often redundantly, by high-quality sensors using a myriad of dissimilar PNT systems, including Very High Frequency Omnidirectional Range Stations (VOR), Distance-Measuring Equipment (DME), inertial systems, and Global Positioning System (GPS) [1]. For GPS in particular, various forms of augmentation systems have been deployed, such as Ground, Space, and Aircraft Based Augmentation Systems, (GBAS, SBAS, and ABAS) to achieve a desired Required Navigation Performance (RNP) for a particular class of operations [2], [3]. Unfortunately, many of these systems are terrestrial-based and become increasingly unavailable or less effective when operating at low altitudes in and around urban canyons [4]. Low altitude flights, such as those for small Unmanned Aircraft Systems (sUAS) or Advanced Air Mobility (AAM), may not have access to the full suite of deployed PNT sources or their augmentation systems [5]. For these operations, PNT sources are typically limited to inertial systems and Global Navigation Satellite Systems (GNSS). This creates a heavy reliance on GNSS to be the primary means of achieving the required RNP for any given operation. Therefore, finding novel and better ways of improving, modeling and simulating GNSS performance is necessary for enabling low altitude flight operations [6].

One of the dominant error sources contributing to degradation in GNSS/GPS performance at low altitudes is multipath. This occurs as the signals reflect off surfaces, such as buildings, and produce multiple copies of the original transmission. These signals arrive at the receiver with varying delay and a composite of the overall signal is measured at the receiver. Depending on the perturbations that occur, this composite may not contain the direct line of sight (LOS) signal, further degrading the measurement that is made. This phenomenon is commonly experienced in cities due to tall buildings and its mitigation is an ongoing area of study [7]. This paper presents a novel technique for simulating GPS multipath through the modification of the GPS-SDR-SIM open-source software. The demonstrated capability could allow for the development of an agile receiver testing framework and the improved evaluation of multipath mitigating technologies.

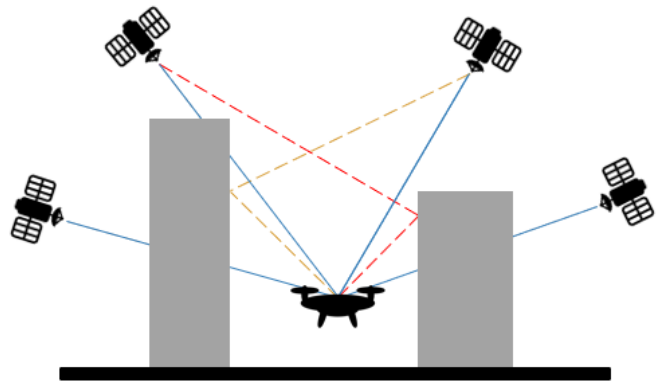


Fig. 1: Notional depiction of multipath in an urban environment.

Open-source tools for generating GPS signals are currently available and can be utilized for the testing and evaluating of GPS receiver equipment. Given predetermined coordinates and orbital parameters, these tools can adequately generate the GPS signals that would be expected at arbitrary locations. That is, the signals generated properly portray what a receiver would expect to measure if physically present at the predetermined location. This capability allows receivers to be tested against and exposed to scenarios that may not be feasible for evaluation outside of a virtual environment. Additionally, while these signals are generated in software, they can be processed by real or software defined receivers, allowing for rapid iteration of development

and testing. The tool used as the basis for this work is GPS-SDR-SIM [8]. This tool can generate GPS signals and implements a variety of error sources inherent to GPS. However, it cannot inject multipath into the signals it generates. A modification was made to this tool enabling it to produce additional copies of GPS signals with variable delay to emulate what happens to GPS signals in the real world as they reflect off of surfaces and arrive at a receiver in place of or alongside the direct GPS signal.

An initial prototype of this work was developed and has demonstrated the ability to produce signals with characteristics consistent with that of multipath experienced in real world scenarios. It has been shown that this generation technique can be successfully performed using a software defined receiver. This technique lowers the bar of entry for advanced simulation and testing of GPS receiver equipment. Further maturation of this work could allow for the development of a GPS receiver testing and evaluation framework and aid in the development of multipath mitigating technologies, amongst many other conceivable use cases.

II. BACKGROUND

In the context of GNSS, multipath occurs when the signal takes multiple paths to reach the user. Under ideal circumstances, the receiver will only measure the direct LOS signal. However, when multipath occurs, the receiver can measure a combination of reflected signals that may or may not include the direct LOS signal [7]. This can greatly affect the quality of the position solution in the case of severe multipath as seen in previous work [9]. A notional example depicting multipath in an urban environment is shown in Fig. 2.

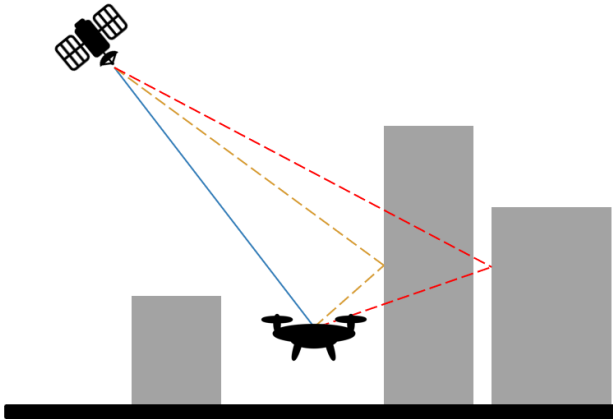


Fig. 2: Depiction of multipath in an urban environment.

However, if the difference between the LOS signals in the multipath signals is large enough, the multipath signal may not be incorporated into the composite measurement that is made by the receiver depending on its design. Fig. 3 shows a notional example depicting how a composite of multiple multipath signals may be interpreted by a receiver. The initial peak represents the LOS signal, while the other peaks represent multipath reflections. The combination of the peaks is depicted

as the composite signal in purple, which when measured by a reference, may result in a delay in the pseudorange relative to the LOS signal.

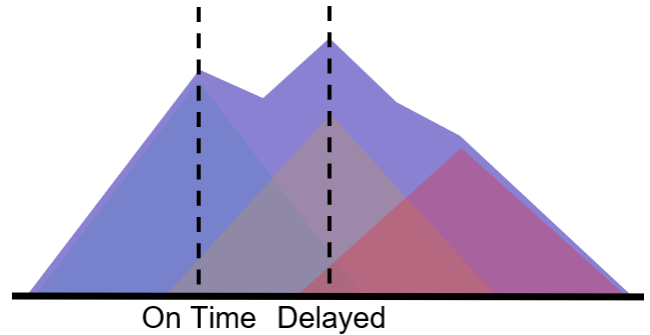


Fig. 3: Depiction of composite of multiple signals measured by the receiver.

Different receivers have varying degrees of multipath susceptibility and understanding these characteristics can help determine the maximum amount a multipath signal can induce onto a pseudorange measurement, and subsequently, onto the position solution.

Unfortunately, these characteristics cannot be obtained outside of highly controlled environments or elaborately contrived multipath conditions. However, with the use of open-source GPS simulator with some minor code modifications, a precise amount of multipath can be induced on a pseudorange measurement simply by duplicating the pseudorange measurement for a particular satellite and delaying it by a specific amount of time. For this we used a modified version of GPS-SDR-SIM. Then impact of these modifications were observed using another open-source program called GNSS-SDR.

A. GPS-SDR-SIM

GPS-SDR-SIM is an open-source application that can be used to generate GPS L1 RF signals [8]. Given a RINEX navigation file, the user is able to specify a specific location and the program will generate signals that would result in a position fix at that predetermined location. The generated RF data can be stored in a binary file or passed to a software defined radio to real-time streaming.

B. GNSS-SDR

GNSS-SDR is another open-source application that can be used to read in GNSS RF signals, process them into a position solution, as well as output the raw satellite measurements in RINEX file format [10]. This software can be used to process RF data collected from live sky constellations to produce a position solution after the fact. However, it can also be used to process the simulated GPS RF data created by GPS-SDR-SIM.

C. GPS-SDR-SIM Modifications

Several modifications were made to the GPS-SDR-SIM application in an effort to emulate the characteristics of

multipath. First, the code was modified to allow for arbitrary delays to be added to the pseudorange of a satellite. Next, a feature was added to enable the pseudorandom code of a satellite to be cloned, essentially allowing for one or more of the simulated satellites to produce the same pseudorandom code, and be identified as the same satellite. When these modifications are combined, this enables the duplication of a specified satellite's signal with a varying delay. When properly configured, this can be used to create signals that have similar characteristics to real world multipath.

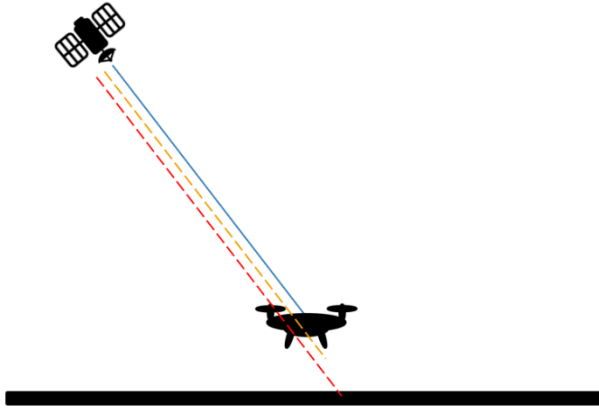


Fig. 4: Depiction of lengthened pseudorange for a particular satellite.

III. EXPERIMENTAL SETUP

The modified version of GPS-SDR-SIM previously described was used to generate GPS signals for three different scenarios. GNSS-SDR was then used to process these signals and produce the raw GPS measurements. For each of the scenarios, 600s of data was collected and analyzed.

The output from these scenarios was analyzed to evaluate the impact the modifications to GPS-SDR-SIM had. For each of the scenarios, the comparisons made are between two satellites, G01 and G02. G01 is the satellite whose pseudorange is being manipulated in the experiments. G02 is an unmodified satellite that, because this is a simulation, was placed into the same orbit as G01 in the simulation's ephemeris. Its purpose is to act as a baseline for comparison with all modifications made to G01. Because they are in the same orbit but are two distinctly different satellites, their unmodified pseudorange should be roughly the same. When modifications are made to G01, they would be readily apparent when compared to G02.

A. Delayed Signal

For this scenario, a 20m delay was added to the pseudorange generated by G01. This was done to evaluate the effectiveness of adding arbitrary delays to a signal. When compared to G02, it is expected that a difference between their measured pseudorange is 20m.

B. Synchronous Signal

For this scenario, no delay was added to G01, however, a clone of G01 was produced and generated in lock step with G01. To verify that the signal is being generated properly it is

expected that G01 is detected by GNSS-SDR and, when compared with G02, there is no difference between the two satellites.

C. Multipath Signal

For this scenario, no delay was introduced to G01, however, a clone of G01 was produced and generated with a 20m delay between it and the original G01 signal. This was done to create a condition in the receiver similar to what is experienced with real world multipath. It is expected that when compared to G02, some amount of delay is experienced somewhere between the original signal and the cloned, multipath signal.

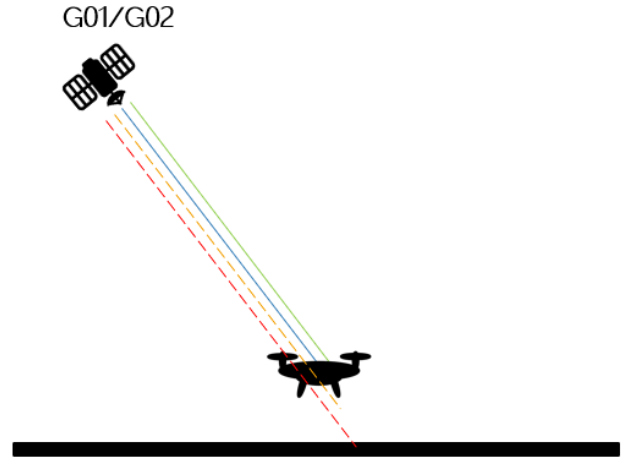


Fig. 5: Depiction of G01 and G02 in the same orbit for baseline pseudorange comparison.

D. Data Processing

Ephemeris data in the form of a RINEX navigation file as well as the desired position for the signals to converge to were supplied to the modified version of GPS-SDR-SIM. The program was run and a binary file containing the RF data from the simulation was created. This file was then input into GNSS-SDR where it was run to compute a position solution and output the raw GPS observables in RINEX file format. The pseudorange measurements contained in the RINEX observation file were then analyzed to evaluate the impact of the modifications made to GPS-SDR-SIM. A block diagram describing the process used can be seen in Fig. 6.

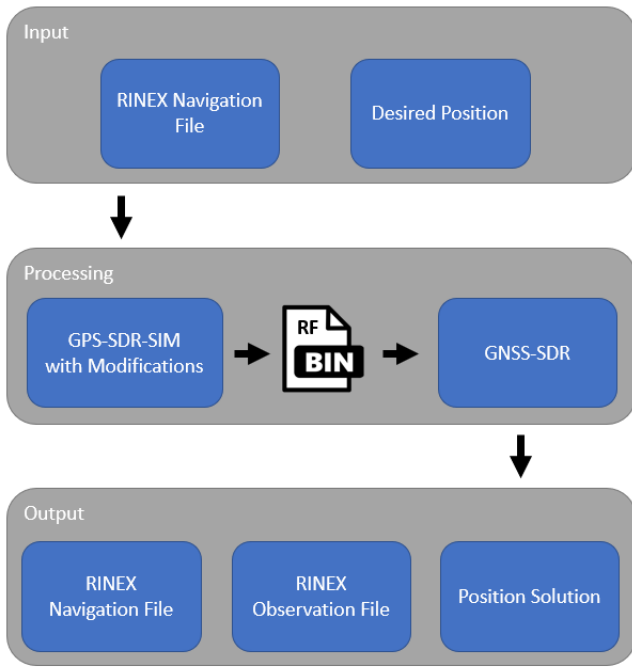


Fig. 6: Block diagram describing the processing of data.

IV. RESULTS

The differences between G01 and G02 were assessed for each of the scenarios over a 600s period of time. A scatter plot and histogram were produced for each of the scenarios with the average difference between the satellite pseudorange being calculated and displayed.

A. Delayed Signal

For this scenario, a 20m delay was added to the pseudorange generated by G01. A scatter plot comparing the difference between the pseudorange measured between G01 and G02 is seen below in Fig. 7.

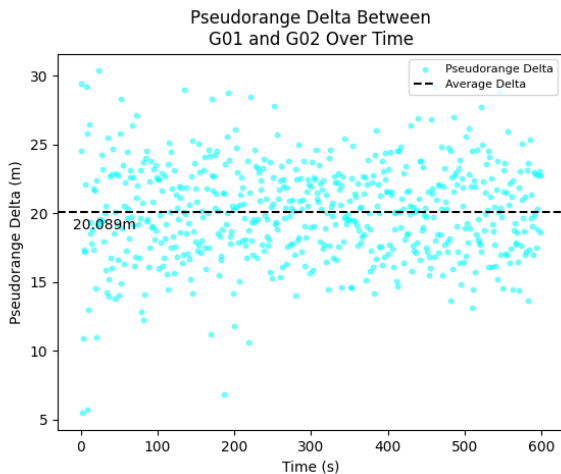


Fig. 7: Scatter plot of the delta between G01 and G02 for the delayed signal scenario.

The average difference between these two satellites is measured to be 20.089m. This value is consistent with the 20m delay introduced to G01 and shows that the delay was added as expected.

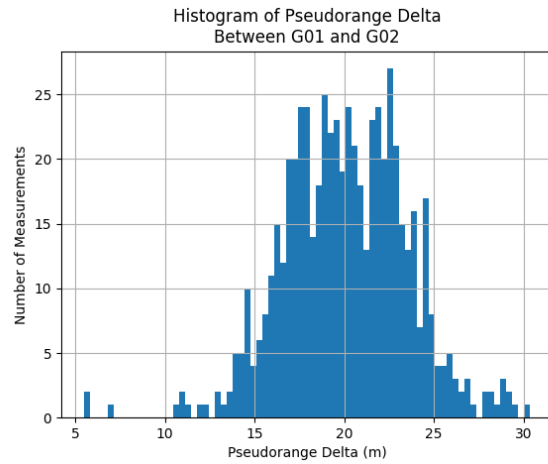


Fig. 8: Histogram of the delta between G01 and G02 for the delayed signal scenario.

A histogram of the pseudorange deltas can be seen in Fig. 8. The distribution appears to be largely gaussian with the expected mean around 20m matching the result observed in the scatter plot.

B. Synchronised Signal

For this scenario, no additional delay was added to G01 but a duplicate of the G01 signal was generated at the same time as the original. The results of this scenario can be seen in Fig. 9.

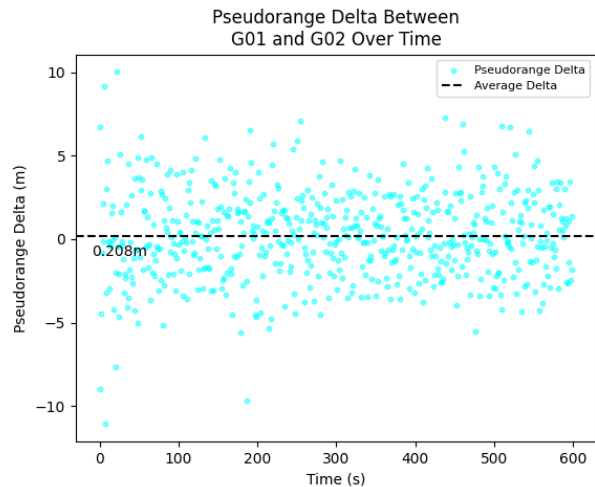


Fig. 9: Scatter plot of the delta between G01 and G02 for the synchronized signal scenario.

The average difference between these two satellites is measured to be 0.208m. This value is consistent with the 0m delay introduced to G01. This shows that the code of G01 was correctly cloned and properly overlaid on the original without corrupting the signal.

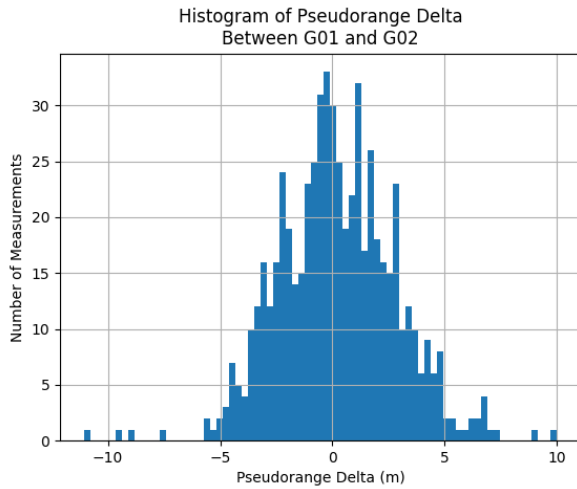


Fig. 10: Histogram of the delta between G01 and G02 for the synchronized signal scenario.

A histogram of the pseudorange deltas can be seen in Fig. 10. The distribution for this scenario again appears to be gaussian and has a mean around 0m. This is consistent with the scatter plot for this scenario.

C. Multipath Signal

For this scenario, no delay was added to G01. A clone of G01 was generated with a 20m delay added to it. In this scenario, there are two G01 signals being generated, the original signal with a 0m delay as well as the cloned signal with a 20m delay. The results of this scenario can be seen in Fig. 11.

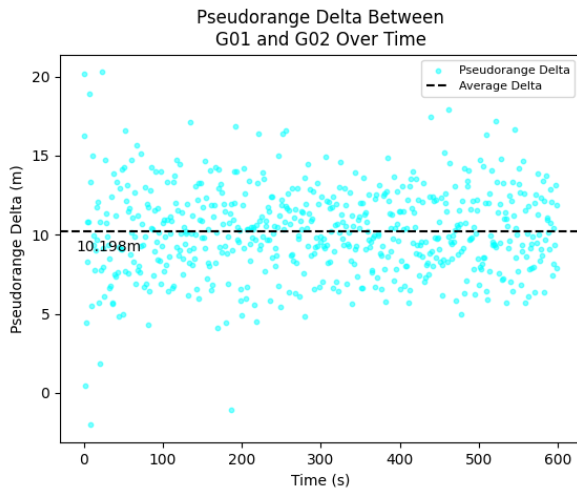


Fig. 11: Scatter plot of the delta between G01 and G02 for the synchronized signal scenario.

The average difference between these two satellites is measured to be 10.198m, in between the delays that were introduced by the two signals for G01.

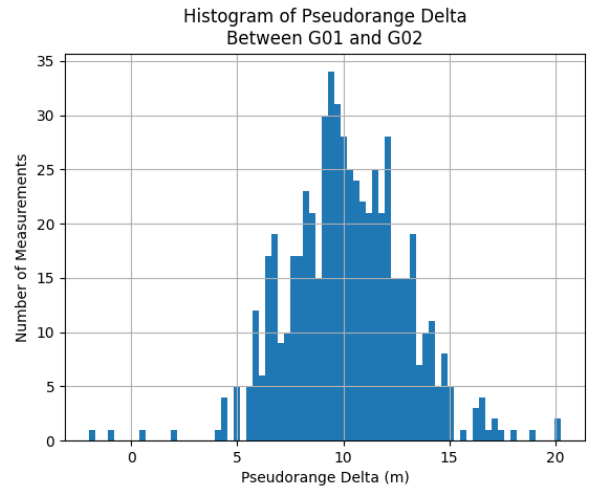


Fig. 12: Histogram of the delta between G01 and G02 for the multipath signal scenario.

The histogram of the pseudorange deltas is shown in Fig. 12. For this scenario, distribution appears to be gaussian with a mean around 10m. This result is consistent with the scatter plot produced above.

For this scenario, the receiver appears to consistently measure a difference between the satellites on average of about 10m even though this specific delta was not explicitly introduced into either of the signals generated for G01. It would appear that a composite of the two signals has been produced in such a way that the receiver is consistently correlating between them. Fig. 13 shows a notional example of what this correlation peak might theoretically look like. This result appears to be consistent with what a receiver could experience when exposed to real world multipath.

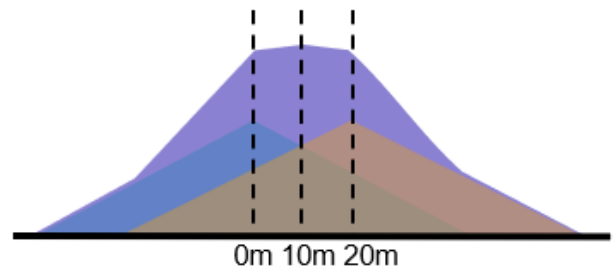


Fig. 13: Depiction of a notional correlation peak composed of a signal with 0 m delay and a signal with 20m delay.

V. CONCLUSIONS AND FUTURE WORK

The modifications made to GPS-SDR-SIM appear to successfully create the characteristics of multipath conditions at the receiver. The results of the experiments show that an arbitrary delay can be introduced into the pseudorange generation of a specific satellite and that the pseudorandom code of a specific satellite can be properly cloned and generated along

with the original. It was found that when these actions are performed at the same time, a composite of the signals is measured at the receiver and closely mimics the expected behaviors of real world multipath. These results show that this technique is an effective means of generating multipath signals with specific attributes under controlled conditions.

Future work could involve further maturation of the modifications of GPS-SDR-SIM to include more precise control over the signals generated, such as the ability to adjust the signal strength of the signals, as well as the introduction of multiple multipath signals. Additionally, while these experiments were conducted using the GNSS-SDR software defined receiver, future work may include the use of physical receivers to assess these effects on real hardware.

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