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August 2025

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Abstract

Multipath is often one of the largest sources contributing to GNSS error in urban environments, making the availability of consistent precise position estimation challenging. While GNSS receiver configurations can be implemented with varying degrees of multipath mitigation techniques, it is still difficult to negate the effect entirely, and can significantly reduce the effectiveness of GNSS as a reliable means of navigation in and around an urban canyon. Therefore, understanding how a receiver reacts to different multipath conditions through modeling and simulation becomes essential in evaluating GNSS's suitability for use in urban environments.

In previous research, we introduced a simplistic GPS multipath simulation using an open-source GPS simulation tool called GPS-SDR-SIM. The program was modified to allow for generation of GPS radio-frequency (RF) signal data that simulates multipath conditions and the effect was evaluated using the software-based GPS receiver toolkit GNSS-SDR. This paper expands on that previous work to include testing and evaluation of physical GPS hardware. The impact of the injected multipath signals is analyzed from the perspective of the physical receiver, and it is shown that they experience similar multipath effects to those observed using the software-based receiver from the previous work.

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1 Introduction

The future of Advanced Air Mobility (AAM) is expected to see many new operations emerge enabling air taxis, Unmanned Aircraft Systems (UAS) package delivery, and other novel use cases. These operations will require increasing levels of autonomy, with many of the critical functions relying heavily on existing Positioning, Navigation, and Timing (PNT) technologies. Global Navigation Satellite Systems (GNSS) are currently used as a primary source of positioning for many existing aviation operations and are often augmented by additional systems, such as Ground, Space, and Aircraft Based Augmentation Systems (GBAS, SBAS, and ABAS), to enable reliable positioning information throughout all phases of flight [1]. However, many AAM operations will take place in and around urban areas where GNSS augmentation techniques become increasingly unavailable and where GNSS performance generally degrades due to several factors.

Multipath is one of the largest sources contributing to GNSS positioning error in urban environments. This phenomenon occurs when the navigation signals from satellites bounce and reflect off buildings and take non-direct paths to the receiver. This can cause a receiver to make erroneous range estimates to satellites as the measurement becomes that of the composite of the originally transmitted satellite signal with that of the multipath signal(s). Furthermore, multipath can affect multiple satellite signals concurrently and with a high level of variation, making the availability of a consistent and accurate position solution challenging [2].

The most pervasively deployed GNSS within the United States is the Global Positioning System (GPS). GPS receiver implementations may have varying degrees of multipath mitigation abilities and can be outfitted with a variety of multipath mitigation techniques, such as purpose-built antenna, and proprietary mitigation techniques [3]. However, it is still difficult to mitigate the effect entirely, significantly reducing the effectiveness of GPS as a reliable means of navigation in and around an urban canyon. Therefore, understanding how a receiver reacts to different multipath conditions through modeling and simulation becomes paramount in evaluating its suitability for use in urban environments and to enable such operations in the first place.

In previous research [4], we introduced a simplistic GPS multipath simulation using an open-source GPS simulation tool called GPS-SDR-SIM. This tool can generate GPS radio-frequency (RF) signal data that converge to a user specified location when processed by a GPS receiver. For that work, the tool was modified to add the ability to produce multiple signals with variable delay from a specific GPS satellite to simulate multipath conditions. To assess the impact of the modifications, the RF data was processed by another tool called GNSS-SDR, an open source GNSS toolkit which acts as a software-based GPS receiver and can process raw GNSS data to report a position solution. This work successfully showed that the added modifications were able to produce multipath conditions at the receiver when using GNSS-SDR to process a position solution.

The previous work was entirely preformed using software tools. This paper will expand on the previous work to include testing and evaluation of physical GPS hardware as well as the expansion of the type of analysis performed to assess the multipath simulation performance. The RF data generated by the modified version of GPS-SDR-SIM will be reproduced using a software defined radio which will be connected to a physical receiver for data collection and processing. The impact of the injected multipath signals will then be analyzed from the perspective of the physical receiver. It is expected that the physical receiver will experience similar multipath effects to those observed using the software-based receiver in the previous work.

2 Background

One of the larger obstacles for GNSS positioning in an urban environment is signal multipath [2]. This occurs when GNSS signals take multiple paths to reach the receiver, due to reflection or obstruction, and can significantly degrade the quality for the computed solution. Under ideal conditions, a receiver will only measure the direct line-of-sight (LOS) signal from the transmitting satellite and the direct time of flight is estimated. However, in the case of multipath, a receiver can measure a combination of the true LOS signal with one or more reflected signals. It is also possible that the direct LOS signal is not present, resulting in measurements that only contain the indirect non-line-of-sight (NLOS) signal(s) [2]. When either of these cases occur, it can greatly affect the quality of the position solution, which has been documented in previous work [5, 6]. An image depicting multipath in an urban environment can be seen below in Figure 1.

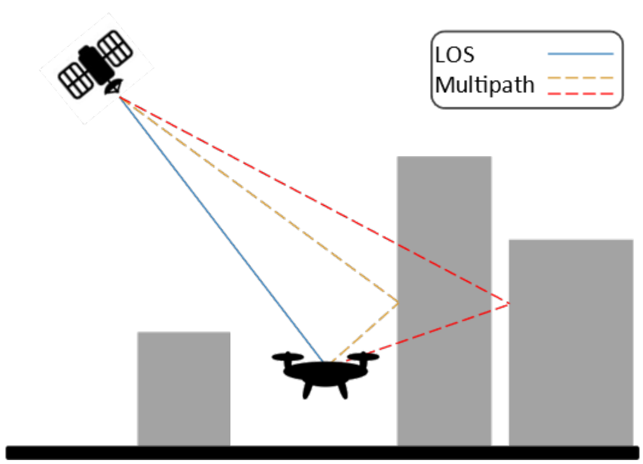

Figure 1: Depiction of multipath in an urban environment showing notional LOS and multipath signal paths.

When multipath is present, the receiver will correlate on the composite of the signal(s) received. This can vary significantly and in ways that can be difficult to predict. Figure 2 shows a notional example depicting how the correlation peak of several multipath signals may be interpreted as a composite by a receiver. The left most peak represents the LOS signal, arriving on time as expected, while the other peaks represent multipath reflections. The combined correlation is shown in purple as the composite of the received signals. As depicted, this composite would be measured as a delay relative to the intended LOS signal.

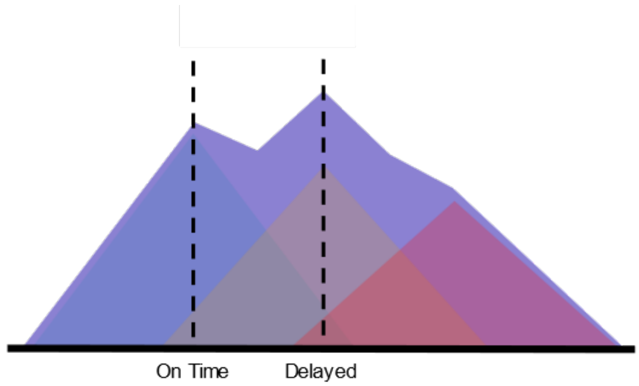

Figure 2: Depiction of composite of multiple signals measured by the receiver.

Receivers can be designed and outfitted with varying degrees of multipath mitigation elements to suppress the effects of multipath. However, the effect can be difficult to fully eliminate, and mitigation techniques vary from receiver to receiver. Understanding how well a receiver is able to mitigate multipath can better help determine which configurations are best for operating in environments that are highly multipath susceptible, such as in and around an urban canyon.

Often, a receiver's multipath mitigation abilities are not immediately apparent, and this type of characterization can be difficult to determine outside of elaborately constructed environments or contrived multipath conditions. However, there are open-source tools that can be used to generate GPS signals for lab testing such as GPS-SDR-SIM. While this software does not have the ability to produce or simulate multipath, modifications were made to the tool to allow for the introduction of a specific amount of multipath on the generated signals. This was done by duplicating the signal of a particular satellite, then delaying it by a specific amount of time. The impact these modifications had on a simulated GPS receiver was shown in previous work [4]. This paper will evaluate the effects on physical receivers.

2.1 GPS-SDR-SIM

GPS-SDR-SIM is an open-source software that is able to generate GPS L1 RF signals [7]. When supplied with a RINEX navigation file containing the desired GPS orbital constellation and a desired position, the software can generate the baseband signals that would results in a GPS receiver converging to that desired position. The generated RF data can be stored in a binary file or streamed to a software defined radio for real-time playback of the generated data.

2.2 GPS-SDR-SIM Modifications

While GPS-SDR-SIM is quite capable out of the box, it does not have the ability to add or simulate multipath. To address this, several modifications were made to GPS-SDR-SIM to introduce this capability [4]. First, the ability to add arbitrary delays to specific satellite signals was added, allowing for the pseudoranges of a satellite to be lengthened or reduced by a user specified amount. This introduces an intentional bias, but not necessarily multipath interference. Then, modifications were made to allow for different satellites to produce the same PRN signal. This allows for one or more of the simulated satellites to produce the same signal and be identified as the same satellite by a receiver. When combined, these modifications produce the duplication of a satellite's signal and allow for one or more of these signals to be delayed. By properly configuring these two effects, and by using an ephemeris with multiple satellites in the same orbit, conditions can be created that have similar characteristics to real world multipath.

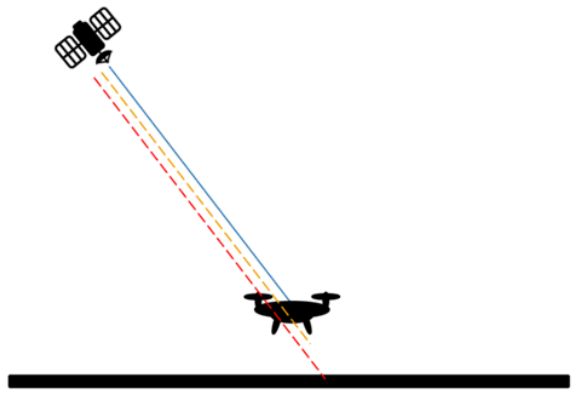

Figure 3: Depiction of multiple pseudoranges with varying lengths being emitted from the same satellite.

3 Experimental Setup

To evaluate the impact that the modifications had on physical receivers, a RINEX navigation file was constructed with multiple satellites occupying the same orbit. This created a baseline satellite that can be used to directly compare the measurements of the modified satellite against. GPS-SDR-SIM used this ephemeris to generate the RF data for three different scenarios, which will be referred to as delay, synchronous, and multipath. The RF data for each of these scenarios was then transmitted to two different GNSS receivers and the impact of the simulated signals was observed by comparing measurements collected from each receiver's log files for each scenario. A data collection script was written to orchestrate and coordinate the generation, playback, data collection scenarios and processing of data for analysis.

3.1 Hardware and Software

The RF data created by GPS-SDR-SIM was transmitted using a HackRF One [8] which was connected to the GNSS receivers under test. The antenna cable from the HackRF One was connected to a DC block along with an attenuator to properly condition the signal going into the receivers. For this experiment, the u-blox 6M [9] and u-blox F9P [10] receivers were used, with each receiver configured to output the raw measurements they observed in the form of a ubx file. After the playback was finished, the ubx files were converted to the RINEX observation file format using RTKLIB [11]. The high-level process can be seen in Figure 4 below.

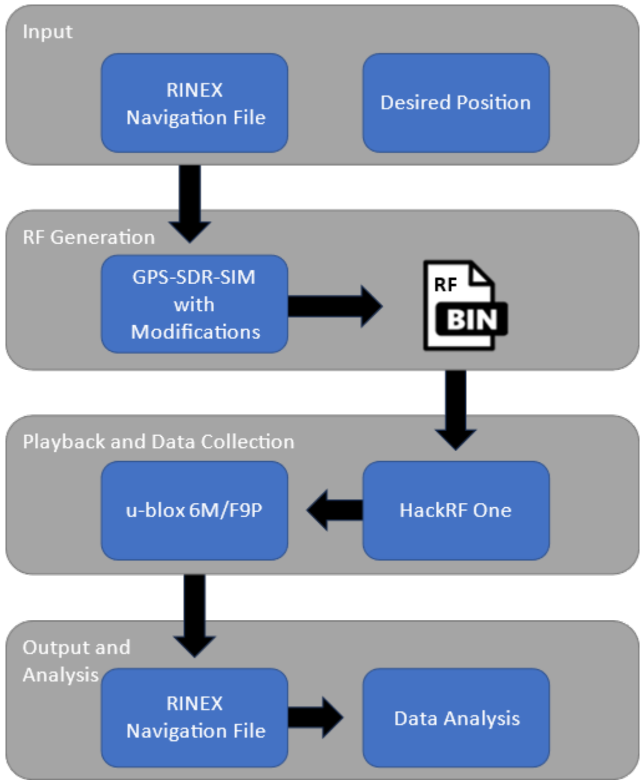

Figure 4: Block diagram of experimental setup.

Additionally, while the HackRF One is capable of producing the GPS signals generated by GPS_SDR_SIM, real GPS satellites, and indirectly GPS receivers, rely on precise but costly atomic clocks. For this reason, the HackRF was outfitted with the Nooelec Tiny TCXO [12] temperature compensated crystal oscillator to produce better results than what would otherwise be achievable using the HackRF One's built-in crystal oscillator.

3.2 Data Generation and Collection

3.2.1 Ephemeris

For the experiments presented in the paper, the ephemeris data was constructed with 2-3 satellites occupying the same orbit. Each satellite was set to the PRN of either G01 or G02 and was placed there to serve one of several purposes:

- Baseline satellite: The baseline satellite was used to directly compare the measurements of the modified satellite(s) against and was given the PRN for G02.

- LOS satellite: This satellite was used to represent the LOS satellite for the experiment. It was given the PRN of G01 and did not have additional delays added to it.

- Multipath satellite: This satellite was used as the multipath satellite. It also shared the PRN of G01 and may have an additional delay added to it. This satellite was used to produce multipath effects for G01 when combine with the LOS satellite.

The baseline satellite was always enabled for comparison against one or more of the other satellites. However, depending on the scenario, the LOS and/or multipath satellite may or may not have been present to achieve the scenario's objectives.

Normally, many correction terms would need to be calculated and removed from a receiver's pseudorange measurements prior to being use in GNSS positioning [3]. However, by leveraging satellites in a shared orbit, these error terms are negated when comparing their pseudorange directly against each other. This allows for direct observation of the simulated multipath introduced simply by subtracting the measurements of the pseudoranges measured for G01 and G02. An image depicting this configuration can be seen in Figure 5.

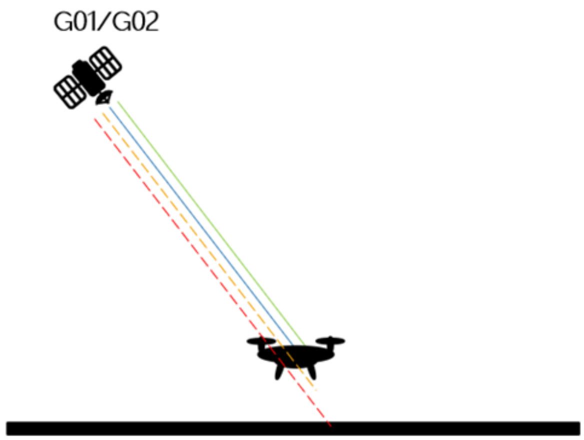

Figure 5: Depiction of G01 and G02 in the same orbit for baseline pseudorange comparison.

3.2.2 Signal Generation

This crafted ephemeris was then used by GPS_SDR_SIM to create the RF data for each of the scenarios. Through initial experimentation it was found that a higher sampling rate produced more consistent results on the receiver hardware. This was particularly true for the F9P while the 6M was stable at a lower sample rate. For this reason, a generation and playback rate of 14MS/s was selected for each scenario and receiver. It should be noted that longer length trials of this experiment result in intermittent perturbations of the measured pseudoranges. For this reason, a 100 second window was used across both receivers to isolate the desired effect while preventing introduction of the stability issues into the dataset.

3.3 Scenarios

3.3.1 Delay

For this scenario, both the baseline and multipath satellites were enabled with an additional 40m added to the pseudorange of the multipath satellite (G01). The intent of this scenario was to verify the ability to add delays to a signal. When compared to the baseline satellite (G02), it is expected that the induced delay of 40m will be directly observed.

3.3.2 Synchronous

For this scenario, the LOS satellite (G01) was used with no delay added. However, the multipath satellite (also G01) was also enabled but with no additional delay added. This was intended to verify that the signals are being generated properly and can be interpreted properly if overlayed on top of each other. It is expected that G01 will be tracked by the receivers and, when compared with G02, no difference between the two satellites will be observed. For this scenario, the power level of both the LOS and multipath transmissions were reduced by half so that the composite received contains that same power that would be expected if only a signal satellite was present.

3.3.3 Multipath

For this scenario, both the LOS (G01) and multipath satellites (also G01) were again used. No delay was added to the LOS satellite. However, a 40m delay was added to the multipath satellite. This was done to create a multipath condition at the receiver similar to what might be experienced with real-world multipath. It is expected that when compared to the baseline satellite (G02), some amount of delay will be experienced between the delays of the LOS satellite and multipath satellite.

4 Results

The results presented show the pseudorange delta between G01, which is made up of one or both the LOS and multipath satellites, and G02, which is always the baseline satellite. This same delta was taken for each of the three scenarios and for both u-blox receivers.

4.1 Delayed Signal

For this scenario, an additional delay of 40m was added to the pseudorange generated by G01 using the multipath satellite with no other changes. The difference in the pseudorange measured between G01 and G02 for both receivers can be seen below.

Figure 6 shows the result for the u-blox 6M while Figure 7 shows the results for the u-blox F9P.

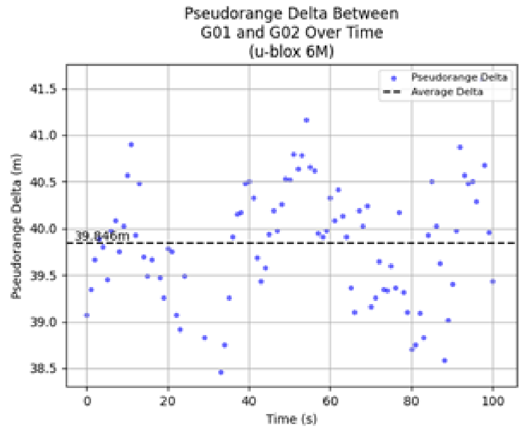

Figure 6: Scatter plot of the delta between G01 and G02 for the delayed signal scenario for the u-blox 6M.

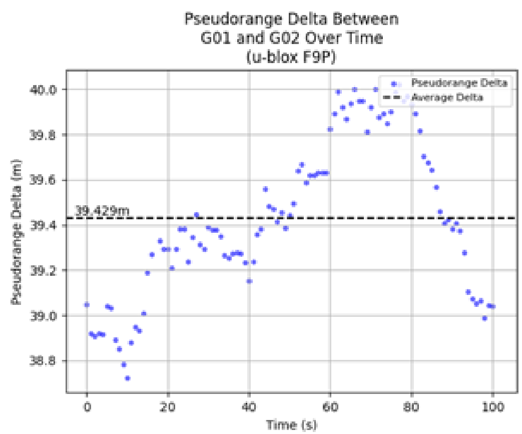

Figure 7: Scatter plot of the delta between G01 and G02 for the delayed signal scenario for the u-blox F9P.

The average difference between these two satellites is measured to be 39.846m for the 6M and 39.429m for the F9P. This value is consistent with the 40m delay introduced to G01 with the multipath satellite. This shows that the delay was added as expected and appears to have the same effect on both receivers.

4.2 Synchronous Signal

For this scenario, both the LOS and multipath satellites produced the PRN signal for G01 with neither introducing a delay. Then the difference between the measured pseudorange between G01 and the baseline satellite of G02 were taken. Figure 8 shows the result for the u-blox 6M and Figure 9 shows the results for the u-blox

F9P.

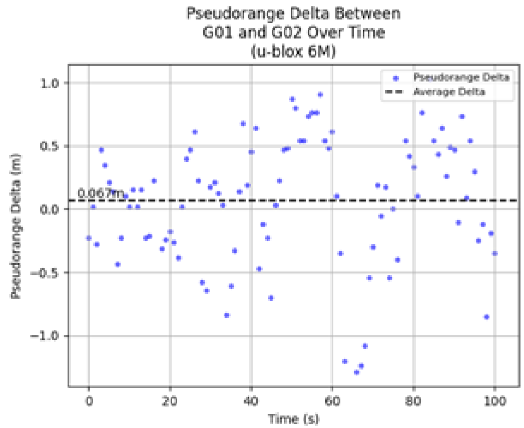

Figure 8: Scatter plot of the delta between G01 and G02 for the synchronous signal scenario for the u-blox 6M.

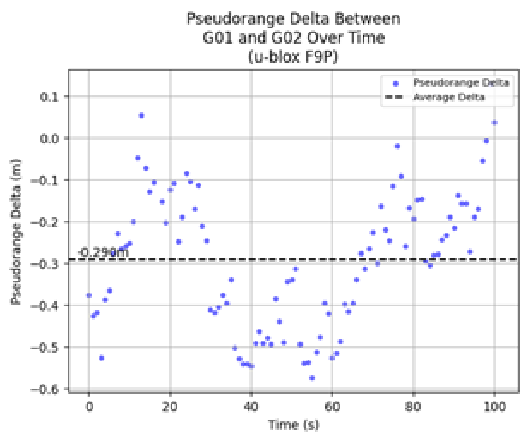

Figure 9: Scatter plot of the delta between G01 and G02 for the synchronous signal scenario for the u-blox F9P.

For this scenario, the average difference between the satellites is measured to be 0.067m for the 6M and -0.290m for the F9P. The measured average is what would be expected in this case as no delay was introduced. However, this shows that the receiver is properly measuring the two synchronous signals, that they are being produced properly, and that both receivers are correctly measuring the signals that are being simulated.

4.3 Multipath Signal

For this scenario, similar to the previous synchronous scenario, both the LOS and the multipath satellites were active on G01. However, in this case, a delay of 40m was introduced on the multipath satellite while the LOS satellite is generated with no delay. The difference between the pseudorange measured for G01 against G02 was then taken. Figure 10 and Figure 11 below show the results for the u-blox 6M and F9P respectively.

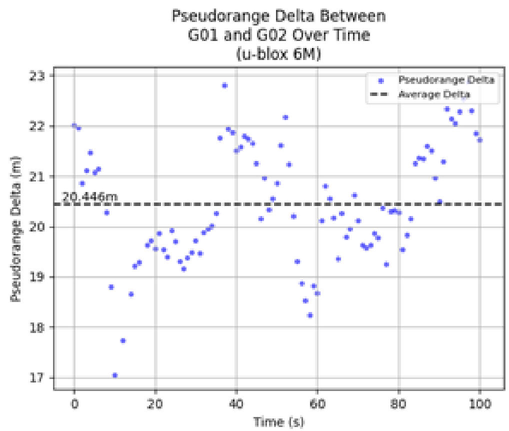

Figure 10: Scatter plot of the delta between G01 and G02 for the multipath signal scenario for the u-blox 6M.

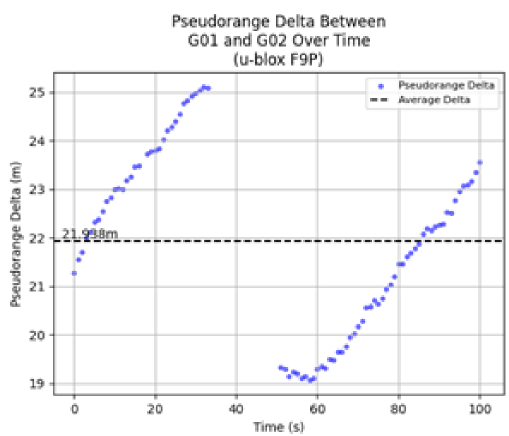

Figure 11: Scatter plot of the delta between G01 and G02 for the multipath signal scenario for the u-blox F9P.

For the multipath scenario, the average difference measured between G01 and G02 was 20.446m for the 6m and 21.938m for the F9P. The average of the difference is about half of the introduced multipath delay of 40 for both scenarios. Both receivers appear to consistently measure an average difference of about 20m between G01 and G02 even though this delay is never specifically generated for either of the G01 signals generated. It appears that the composite of the two G01 signals are being measured in such a way that the receiver is correlating between them. Figure 12 shows an 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.

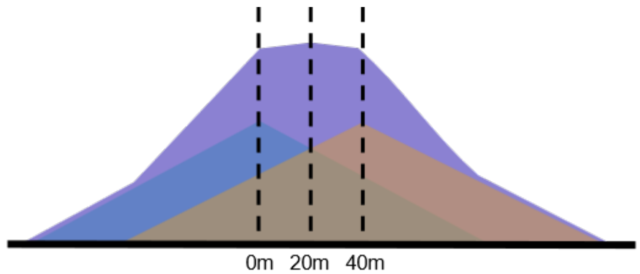

Figure 12: Depiction of a notational correlation peak composed of a signal with 0m delay and a signal with 40m delay.

However, the receivers differ in the variation of the measured pseudorange during the measurement window. The 6M appears to produce a consistent offset which is similar to the data seen in the previous results for this device. While the deltas obtained for the F9P do produce a similar average difference, there is more variation in the data, with the deltas slowly growing and resetting over time. It is possible that the F9P is struggling to consistently track the composite signal created by the interference pattern of the two satellite signals. It may be that this receiver employs a narrower correlator and/or other design features that are resulting in this behavior. Further investigation is required to better understand and characterize this behavior.

Nevertheless, both receivers appear to show a multipath effect when multiple signals of the same PRN are generated. These results, particularly the results obtained by the 6M, closely reproduce what was seen in simulation [4]. The results obtained from the F9P may be starting to reflect differences in the design between the receivers, however, the similarity of the average delta shows that a similar effect is being induced within the two receivers.

5 Conclusions and Future Work

For this work, GPS signals were generated using a modified version GPS-SDR-SIM that allowed for the introduction of duplicated satellite signals with variable pseudorange delays. Experiments were performed using a HackRF One to generate the signals and u-blox 6M and F9P receivers were used to measure the data for delayed, synchronous, and multipath scenarios. The results for the delay scenario showed the expected pseudorange delay, the synchronous scenario showed that the pseudorandom code of two satellites can be correctly constructed and generated at the same time, and the multipath scenario showed that when these actions are performed together, a composite of the signals can be created and measured at the receiver that closely matches the behavior expected in real world multipath. Although the F9P experienced variation and drift in the deltas not seen in the 6M.

These results show that this technique is an effective means of generating multipath signals with specific attributes under controlled conditions. The modifications made to GPS-SDR-SIM have now been tested both in simulation in previous work and using physical hardware with this work. In both cases, it appears to successfully create the characteristics of multipath conditions that would be expected at the receiver.

Future work could involve expanding the types and number receivers included as well as evaluation of different scenarios with further assessment and characterization of the multipath susceptibility. Additionally, exploration into improvement of the SDR's timing reference could be done to assess what impact a better oscillator may have on the performance of the GPS receivers under test. Lastly, evaluation of carrier wave variation on the receiver measurements could be performed to create a more complete and accurate simulation of multipath behavior at the receiver.

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