Analysis of Record and Playback Errors of GPS Signals Caused by the USRP

by

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Abstract

In this thesis, the errors created by the USRP (Universal Software Receiver Platform) during record and playback are analyzed. The USRP is used for jamming, spoofing, and GPS processing, and has recently become widely used for capturing GPS signals for record and playback. However, there has been little research into how the USRP effects signal quality during record and playback.

This thesis is based on the live capture of L1 GPS signals. Data is captured for multiple scenarios in both static and dynamic situations. The signal is split and sent to multiple receivers and the USRP. The data is gathered, parsed, and quantified using statistical analysis for comparison over a broad range of tests.

From the captured signals, statistical analysis is used for a more comprehensive overview of the USRP. Results show that statistical data from playback of GPS signals is reliable in multiple scenarios, thus validation the USRP as an accurate means by which data can be recorded and played back.

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Chapter 1

Introduction/Terms

This thesis will begin by explaining the USRP (Universal Software Radio Peripheral) in depth. Previous research that has influenced this work and vital terms will be defined. This section is concluded with a discussion about the hardware and software to give a better understanding of the equipment used for data collection.

1.1 Motivation

The USRP is used for record and playback of signals in many projects. It is very useful when working with unique signals. Though some noise statistics are known about the USRP, no study has been done on the repercussions of recording and playing back GPS signals. This thesis focuses on live IF (Intermediate Frequency) data and the error or changes the USRP makes to this data during record and playback. The validity of recording and playing back data is verified with this real data.

Because of the many applications in which the USRP is used, there is also a need for an understanding of how different scenarios change the results from the USRP differently. The multiple scenarios used in this thesis represent a subset of data that can be collected by the USRP. Most of these scenarios are changes in hardware during record and playback. In an attempt to keep the experimentation to a level used by most people, this thesis will focus on L1 GPS signals for record and playback.

1.2 Key Terms

In this section important terms used in this thesis are defined and their uses are discussed. There are many components to the USRP that need to be known before using the equipment; this section will break down and define the components of the USRP and their purposes.

The USRP is a widely known, highly used “software radio”, meaning it is software programmable. The USRP has a motherboard with an FPGA (Field Program Gate Array) which can be reprogrammed and has fast computation capabilities. The USRP also requires a daughterboard, which is the customizable front end for this receiver. The motherboard and daughterboard are combined as a completed USRP, which is then connected to a computer in order to record data at high speed via a gigabit ethernet cable. The recording can be sent to the onboard hard drive or external drive via USB 3.0 to be used at a later date. The WBX daughterboard is a broadband front end that can accept frequencies between 50Mhz and 2.2Ghz. It can receive and transmit from the same board and has a bandwidth of 40Mhz. This makes it ideal for GPS because it can cover all GPS frequencies and bandwidths. With multiple USRPs, all GPS frequencies can be captured and played back to create a live sky scenario. This has to be done with multiple USRP’s because the bandwidth does not allow for L1, L2 and L5 to be received simultaneously on one daughterboard.

The FPGA on the motherboard is one of the most important components of the USRP. The FPGA is a reprogrammable hardware chip which can be used many times and in multiple ways. It is a series of silicon gates that can be either opened or closed depending on what is needed. The FPGA is a vital for capturing data at the high sample rate required for GPS.

The clock on the motherboard is used to sample data. The standard USRP clock is a 100 Hz TCXO (Temperature Controlled Crystal Oscillator), and the TCXO measures the oscillation of an open crystal that changes with temperature. The TCXO is one of the least accurate clocks available, and when working with GPS another clock may be needed. The frequency accuracy of the TCXO on the USRP is 2.5 ppm (Parts Per Million) ,which is a measurement of the variation in the clock over time.

The GPSDO is an option that can be added to the USRP. The GPSDO (GPS Disciplined Oscillator) is an OCXO (Oven Controlled Crystal Oscillator) with a GPS receiver to give

GPS time corrections. The OCXO is 100 times more accurate than the TCXO at about .025 ppm for the OCXO by itself. The OCXO outputs a 10 MHz signal which will discipline the TCXO on the motherboard. The GPSDO has a Ublox receiver onboard that GPS time updates; these time updates are used to discipline the onboard OCXO, making it accurate to .01 ppm. The GPSDO is used in experiments for this thesis, and shows a great deal more accuracy for position measurements.

A completely external clock called the CSAC (Chip Scaled Atomic Clock) is also investigated. The CSAC is much more accurate than the OCXO. This clock uses cesium atoms to keep time instead of an oscillating crystal. This clock, though much more accurate than the GPSDO, may not change the position accuracy from the USRP. This clock will also be tested and compared to the TCXO and GPSDO.

There are many designations of time when working with GPS. The two used in this work are GPS time and UTC time. The GPS time is of the format week number and week seconds. This gives the number of weeks since the beginning of GPS time and the number of seconds from midnight Sunday of a new week. UTC (Coordinated Universal Time) or GMT (Greenwich Mean Time) is the worldwide standard time. This time is based on a 24 hour clock and is much easier to keep track of than GPS time. Both types of time are important in this project to keep track of the data being captured to make sure everything is taken at the same time.

When calculating GPS positions multiple lower level measurements are used. In this thesis, some of these measurements are explored to get a more comprehensive overview of the error created by the USRP. The first measurements discussed are pseudoranges. The pseudoranges are used to calculate the position of the GPS receiver. The pseudorange is a range between the satellite and receiver plus errors that will be discussed in Section 1.4. These measurements are used in most receivers, but the Ublox does not automatically output these measurements. To record the pseudoranges a software package called Go-GPS is used in congruence with Matlab.

Another measurement used in this thesis is the doppler measurement. The doppler measurement is the quantification of doppler shift from the motion of the satellites. The doppler measurements are explored in this thesis because they are much noisier than the pseudorange measurements. The doppler measurements are measurements used to calculate the velocity of the receiver. The final measurement used is the carrier to noise measurement. This is the ratio of the signal power to the noise power. This measurement can show a broad spectrum of the noise and how the USRP increases the noise during record and playback.

1.3 Previous Work

The USRP is a simplistic piece of hardware that is inexpensive to purchase. Because of this, it has been used by many people for many different applications. The papers discussed in this section provide concepts for testing and for future work.

As is well known, GPS signals have error associated with them. Many of the errors are modeled while others are incapable of being modeled. To understand the errors created by the USRP it is first imperative to get a basic understanding of the errors on the GPS signals. One paper that discusses this is [16], which goes into details about the error statistics and types on the pseudoranges and how the error changes with different types of receivers. The paper also gives statistics of the Markov processes they use to model the error. The errors have been tabulated in Table 1.1 from [16]. Each statistic shown in Table 1.1 corresponds to error in the pseudoranges caused by the individual sources mentioned. Looking at the pseudoranges can show other sources of error when the known errors can be accounted for.

Table 1.1: Error Model Statistics for Paper Markov Processes

Error Parameter	Std. Dev. (meters)	Time(s)
Ephemeris	3.0	1800
Ionosphere	5.0	1800
Troposphere	2.0	3600
Multipath, C/A Standard	5.0	600
Multipath, C/A Narrow	0.25	600
Multipath, P	1.0	600
Multipath, L1 carrier	0.048	600
Selective Availability	30.0	180

To start the work with the USRP, a proper setup was required. Because the USRP is inexpensive and not explicitly designed to record GPS, some modifications were required to the USRP. First, a daughterboard was chosen based on bandwidth and record and playback capability. The WBX daughterboard was chosen and validated in [6],which also shows Matlab as a usable software package and useful when trying to simulate GPS signals in the future.

In the past, before the availability of the USRP N210, the standard USRP was used. To get a signal that is viable the author in [19] required the use of an external down converter for the signal. The work converted the signal from the 1.5 GHz to the IF frequency 915 MHz. Their daughterboard takes in a frequency ranged of 750-1050 MHz and mixes it down to baseband. They up convert the base band data in Matlab to an IF of 1 MHz as shown in Equation (1.1) where $f_m = 1MHz$ and $f_s = 4MHz$ the up conversion allows the multiplication coefficients to be zeroes and ±1.

$$y = Icos(\frac{2\pi n f_m}{f_s}) - Qsin(\frac{2\pi n f_m}{f_s}) \tag{1.1}$$

As noted, the USRP signal needs to be slightly modified for it to be useful when recorded. Many different methods are used, most of which involve amplification and filtering as noted in [11]. A method similar to [11] with a 30dB low noise amplifier and a band pass filter was initially used. Through experimental means an alternative method used with one active antenna was devised.

Some of the error created by the USRP is created in the following ways: the sampling procedure, the process noise in the USRP, and the clock noise of the USRP. When looking into these various errors, research was initially conducted on the effect of clock noise; this was chosen as the first study for noise because of its significance in GPS solutions. Many papers discuss the error created by the USRP clock during sampling. One such paper, [18], discusses a study done on L1 and L2 from one satellite that compares measurements capture from the TCXO and OCXO. Building on this with this in [10] discusses a software receiver and the differences between external clock options. The frequency instability of an oscillator in terms of instantaneous, normalized frequency deviation y(t) is in Equation 1.2, where f(t) is the instantaneous frequency and f_0 is the nominal frequency. In [10] they discuss where errors occur in a software receiver.

$$y(t) = \frac{f(t) - f_0}{f_0}, \tag{1.2}$$

$$\Delta f_{IF} = f_{IF} - \hat{f_{IF}} = r\Delta f_S + \delta \tag{1.3}$$

In Equation 1.3 the δ is error due to imperfection of the frequency synthesizer, which is basically error caused by the clock. The research in [10] uses a simulator, so any error in the wave is synthesized and can be set to zero. Therefore the main error is the clock error from the simulator and receiver. The clock error can be modeled in discrete time using the first order Taylor series (Equation 1.4) where y_0 is the initial fractional frequency error, z_0 is the initial linear frequency drift rate, τ is the time interval of the frequency error measurements, w_n is the frequency process noise. the fractional frequency deviation measurement s_n is the sum of y_n the frequency deviation and the zero mean measurement noise v_n.

$$y_n = y_0 + z_0\tau n + w_n \tag{1.4}$$

$$\hat{y}_n = \sum_{i=0}^{N-1} h_{1i} s_{n-i} \tag{1.5}$$

From this the clock mode estimation (Equation 1.5) is derived, and from the tests run, the statistics for all three types of clocks used is shown in Table 1.2.

Table 1.2: Averaged Frequency Offset and Drift Rate

Oscillator	Rb	OCXO	TCXO
Mean (y_n)	-4.08e-10	-4.48e-8	6.63e-7
Mean (z_n)	1.0363e-15	-2.6299e-14	6.9867e-13

This table shows the average error from the clock. As can be seen, the TCXO is about 10 times worse than the OCXO. This will translate to error in position calculations because of the need for accurate timing when doing GPS calculations.

Although in [10] the writers discussed a rubidium oscillator as the atomic clock, this thesis uses a CSAC (Chip Scale Atomic Clock). For the statistics and background on the CSAC, the Symmetricon paper [12] was studied. The idea behind the CSAC clock was to get a small very accurate clock that does not use a significant amount of power. The CSAC has a low power TCXO that outputs a signal to the microwave synthesizer that keeps the time with cesium atoms. For a short time span the CSAC has an Alan variance with distribution medians for a time constant of 10 seconds of $2.4X10^{-11}$. This is comparable to the required timing accuracy of GPS of nanosecond level.

There is always a need for low cost GPS simulators. Because this thesis focuses on the noise created by the USRP, one of the goal uses for this thesis will be with a GPS simulator using the USRP. Navsys has software and hardware packages that can be used for recording, playing back, jamming, spoofing and simulating GPS with the USRP. The paper focuses on the uses of Matlab in [7], [5], and [4]. Each paper discussed advancements in the area of simulation and recording. In [5] the paper focuses on the simulation of more complicated signals including scintillation, but the drawback is the information has to be dealt with digitally. This hardware package cannot playback, on the other hand in [4] a hybrid simulator/receiver is discussed which can playback recorded data but not simulated data. From these papers a need for simplistic simulators that can playback data to a hardware receiver is discovered.

Other papers focus on methods to interfere with the GPS signal. There is always needs for a low cost, portable, and flexible GNSS signal and interference signal generator. The main receiver used to verify the ability of the interference signal generator is a Novatel. In the paper [8] many signals were simulated to show that there are a number of possibilities for simulations.

Jamming is not only an issue with GPS, it also is an issue in standard radio. The methods in [15] use a spread spectrum technique to make the signal more robust. The USRP is used to place the code on the broadband signal because of its ability to process data at such a fast pace. This paper concluded that the USRP is a good multiuse platform.

The USRP is also being used for mitigating RF interferences. In the system presented in [13] a USRP1 with a WBX daughterboard is used to identify the interference signals and remove it. These experiments were done on the GPS frequency but at a much higher power than GPS. A BPSK (Binary Phase Shift Keying) signal is created and transmitted with a second signal attempting to corrupt it. The algorithm used has a reference signal vector, which the cost function is based off of. The main disadvantage of this is that the profile required for the USRP to recognize the proper signal will knock out more powerful signals.

All GPS signals are encoded with Pseudorandom noise, in the paper [14] they discuss the errors caused by I/Q imbalances created by the USRP. In this paper the errors discussed are caused by encoded messages over multiple frequencies. This is important when dealing with Dual Frequency (L1/L2) messages and shows another method of USRP error creation.

1.4 GPS Background Information

As mentioned earlier this thesis details how the USRP works with GPS record and playback. To understand how this works, some basic GPS needs to be discussed.

1.4.1 GPS Position Calculation

To get a GPS position solution, a method called trilateralization is used. For a position solution from the signals, four GPS satellites are required. These satellite positions are calculated from the ephemeris that they transmit. Knowing the position of the satellites, clock bias of the satellites, and the pseudoranges between each satellite and receiver, a position solution can be calculated. The general way to solve for the position solutions is shown in formula in Equations (1.6 - 1.13). The actual range between the receiver and the satellite positions is seen in (1.6). This range is calculated from the satellite positions and an estimate of the receiver position.

$$range = \sqrt{(\hat{x} - satposition_x)^2 + (\hat{y} - satposition_y)^2 + (\hat{z} - satposition_z)^2} \tag{1.6}$$

From this range calculated in (1.6) and the positions of the satellites and receiver the unit vectors to each satellite are calculated. The unit vectors seen in (1.7) are used in the least squares calculations to estimate the receiver positions.

$$\begin{bmatrix} ux \\ uy \\ uz \end{bmatrix} = \begin{bmatrix} (\hat{x} - satposition_x)/range \\ (\hat{y} - satposition_y)/range \\ (\hat{z} - satposition_z)/range \end{bmatrix} \tag{1.7}$$

The H matrix (1.8) is a matrix of the unit vectors to each satellite and a row of ones for estimation of the clock bias.

$$H = \begin{bmatrix} ux_1 & uy_1 & uz_1 & 1 \\ \vdots & \vdots & \vdots & \vdots \\ ux_n & uy_n & uz_n & 1 \end{bmatrix} \tag{1.8}$$

The position vector in Equation (1.9) plus the clock term is estimated each iteration. With the least squares method the position solution is generally acceptable within five iteration.

$$\hat{pos} = \begin{bmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \\ cdt \end{bmatrix} \tag{1.9}$$

The estimated pseudoranges are calculated in Equation (1.10) where the cdt is the final part of the vector in Equation (1.9).

$$\hat{\rho} = \sqrt{(\hat{x} - satposition_x)^2 + (\hat{y} - satposition_y)^2 + (\hat{z} - satposition_z)^2} + cdt \tag{1.10}$$

The change in pseudorange shown in Equation (1.11) is used with the H matrix as seen in Equation (1.12) to calculate the change in receiver position.

$$\nabla\rho = \hat{\rho} - (\rho + (svn\,clock * c)) \tag{1.11}$$

$$\nabla pos = ((H^T H)^{-1} H^T)\nabla\rho \tag{1.12}$$

The new position is then calculated as seen in Equation (1.13).

$$\hat{pos} = \hat{pos} - \nabla pos \tag{1.13}$$

Where *range* is the change in position between a satellite and the receiver, $\begin{bmatrix} ux \\ uy \\ uz \end{bmatrix}$ are the unit vectors from the receiver to the visible satellites, H is the geometry matrix, $\hat{pos}$ is the estimated receiver position and receiver clock bias, $\hat{\rho}$ is the estimated pseudorange with the clock bias ,$\nabla\rho$ is the difference between the estimated and measured pseudoranges, and ∇pos is a change of receiver position for updating the new estimated receiver position. The Equations (1.6 - 1.13) are calculated in a iterative loop calculating the position within a few meters. This simple method of calculating a position is based on iterative least squares, which will give an accurate position solution in approximately 10 iterations if the initial position is the center of the earth. Other methods are available that handle errors differently, but this method is the simplest.

1.4.2 GPS Signal Structure

The GPS signal is transmitted by a satellite that is in orbit. Each satellite transmits a signal that has unique data and code on it. Each satellite sends a signal out, for this thesis only L1 will be discussed, which is 1.575 GHz. This carrier signal wave contains a digital code and data signals. The other two signals are placed on the carrier signal by phase modulation. This means that the signal will flip 180 degrees when a bit is present. The three signals are shown in Figure 1.1 but are not to scale.

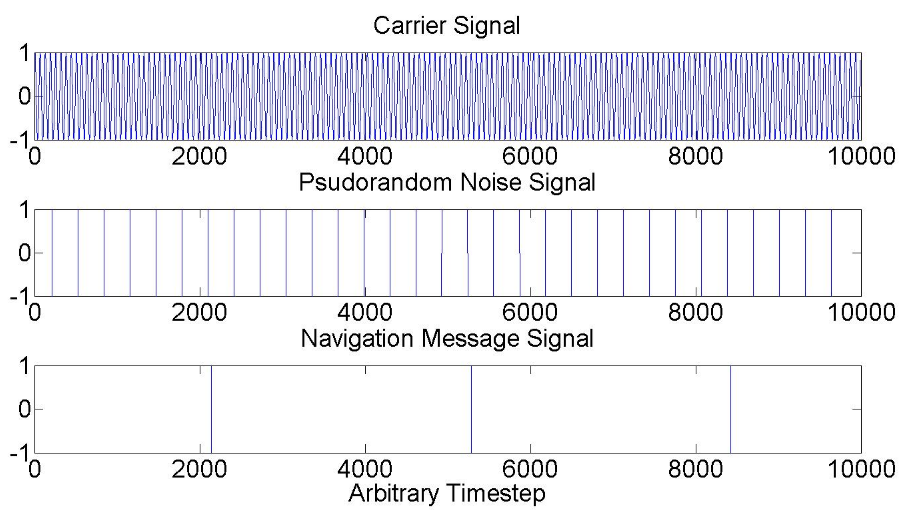

Figure 1.1: Graphical Example of the Three GPS Signals

The pseudorandom code is created using a gold code that multiplies an 8 bit binary signal in a specific sequence giving a unique random looking code. This code 1023 bits long and is transmitted at 1.023 MHz causing it to cycle every millisecond. The range calculated using this signal signal is called the pseudorange. The pseudorange measurement is used to calculate the receiver position to an accuracy of ~3 meters.

The pseudorange must be calculated using the navigation message. The navigation message is transmitted even slower than the code and one bit of the navigation method is received every two milliseconds. The navigation message consists of five subframes seen in Figure 5.3 . Each subframe contains different information; the first three give ephemeris data with which the user can calculate satellite positions. Subframes four and five contain the almanac, which take 12 minutes to receive. The ephemeris takes between 18 and 30 seconds of constant reception to receive. Only the ephemeris is needed to calculate the position but the almanac gives vital information for a better position solution. The subframe structure is seen in Figure 5.3 later in this thesis.

The signal structure is seen in Equations (1.14 - 1.16). These equations show the complete signals for RF and IF signals.

$$s_{RF}(t) = \sqrt{2P_{RF}(t)}D[t - \tau_{g,RF}(t)]C[t - \tau_{g,RF}(t)].cos\{2\pi f_L[t - \tau_{p,RF}(t)] + \phi_{0,RF}\} \tag{1.14}$$

$$s_{IF}(t) = \sqrt{2P_{IF}(t)}D[t - \tau_{g,IF}(t)]C[t - \tau_{g,IF}(t)].cos\{2\pi \int f_{IF}(t)dt - 2\pi f_L \tau_{p,IF}(t) + \phi_{0,IF}\} \tag{1.15}$$

$$s_{IF}(t) = \sqrt{2P_{IF}(t)}D[t-\tau_{g,IF}(t)]C[t-\tau_{g,IF}(t)].cos\{2\pi[\hat{f_{IF}}t + \int \Delta f_{IF}(t)dt - f_L \tau_{p,IF}(t) + \phi_{0,IF}\} \tag{1.16}$$

In this signal structure, t is simulated receiving time, $P_{RF}(t)$ is the received RF signal power for the sv, $D(t)$ is the navigation digital signal, $C(t)$ is the spreading code signal, $\tau_{g,RF}(t)$ is the delay of the base band signal (group delay), $\tau_{p,RF}(t)$ is the delay of the carrier (phase delay), f_L is the carrier frequency, and $\phi_{0,RF}$ is the initial carrier phase.

1.5 Contributions

This thesis proves the viability of the USRP. Using experimental data and methods previously mentioned, a better understanding of the error caused by the USRP is obtained.

This thesis also shows how the USRP responds to different clock disciplines including TCXO, OCXO, and CSAC. Different acquisition scenarios including static, dynamic and high dynamic errors are also examined. Finally the repeatability of the USRP is validated so one data file can be used multiple ways.

1.6 Thesis Outline

Because of the versatility of the USRP many tests were executed to look at the errors caused by the USRP in many ways. In this thesis, the USRP will be discussed in both static and dynamic scenarios. The majority of the data is collected statically because of the stability and controllability of static environments. The first two chapters discuss the background of the USRP and how it was specifically set up for this thesis. The third chapter introduces the static data collected. Multiple clocking options will be discussed including: using the onboard TCXO(Temperature Controlled Crystal Oscillator), then using the increased accuracy of the GPSDO(GPS Disciplined Oscillator), and the most accurate CSAC(Chip Scale Atomic Clock). After doing these tests the USRP repeatability will be discussed along with observations made of measurements the pseudorange level.

Chapter four discusses the errors created by the USRP from dynamic data. The dynamic testing is split up into two sections; first is the slower dynamic testing and second is the high dynamic where higher speeds and turns are executed. Finally, data collected with a software receiver is discussed in which the workings of the receiver and discoveries during the testing process are explained. After the results are discussed, conclusions are drawn in chapter five with future work in chapter six.

Chapter 2

USRP Background

In this chapter the hardware of the USRP and the software to interface to the device is explained. The USRP uses a simplistic design so it can be used over many different spectrum. The use of a daughterboard slot makes it configurable to most signals. It also has software designed with the USRP in mind called GNU Radio. This software, in addition to UHD (USRP Hardware Driver), allows for the simplistic interface and use of the USRP.

2.1 USRP Hardware

The USRP is based off the design of the FPGA, which is a reprogrammable piece of hardware. The FPGA used in the USRP is Spartan 3A-DSP 3400 FPGA as seen on the data sheet [17]. The FPGA on the USRP is flashed with UHD because of its use in GNU Radio. Along with the FPGA, each USRP requires a daughterboard as an instrument to narrow down the bandwidth of the signal.

The daughterboard used in this thesis is the WBX board. The WBX daughterboard is chosen for two separate reasons. First is its ability to cover both L1 and L2 frequencies within its bandwidth, and second is its ability to record and playback from one daughterboard. An alternate board, the DBSRX2 daughterboard, has been used in many GPS recording circumstances. The WBX is chosen over the DBSRX2 daughterboard because the DBSRX2 board allows for recording only. However the DBSRX2 board, does have has a larger bandwidth and powers the antenna. The WBX has a usable bandwidth of 40MHz that can be sampled and a range from 50MHz to 2.2GHz, which gives the capability to capture L1, L2 and L5 at separate times.

Additionally, a GPSDO is connected to the USRP motherboard as an option to increase clock accuracy. As mentioned earlier, the clock on the USRP motherboard is a standard TCXO which is vastly improved upon by the OCXO on the GPSDO board. In addition to having a more accurate clock, the GPSDO also has an Ublox receiver that calculates GPS time corrections. These time corrections are used to discipline its OCXO, which disciplines the TCXO on the USRP. As shown later, the best results are seen when using the GPSDO as a time source and clock source. The time source is an input for a 10MHz signal and the clock source is a pulse per second used to synchronize multiple USRP's if required.

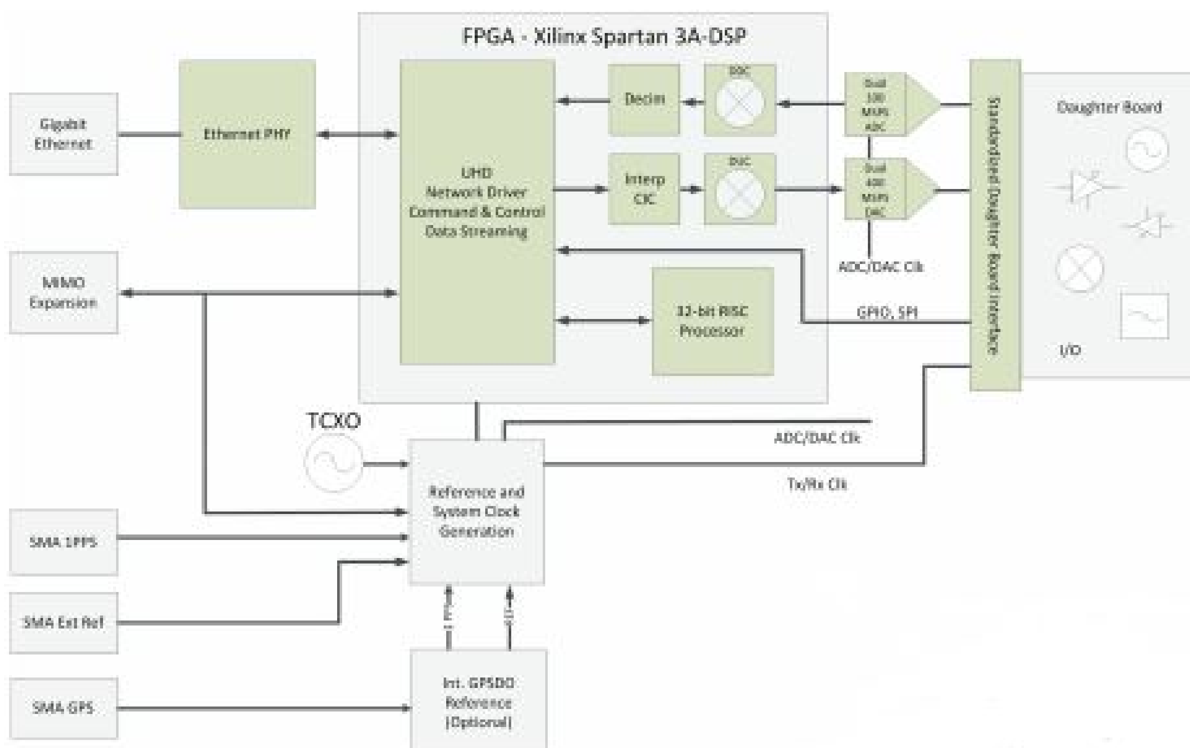

Figure 2.1: USRP Circuit Diagram

Figure 2.1 shows a high level layout of the USRP N210. Two main things are shown in this figure. The first is the flow inside the USRP which magnifies the importance of the FPGA showing most signals going through it. The second piece of information from Figure 2.1 is the flow of timing which is vital to know when making changes to the mother and daughterboards.

The USRP mixes the GPS signal from the 1.5 GHz down to a base band, meaning the IF signal that is recorded is actually 0. The USRP then samples the ~1 MHz bandwidth which is required to receive the whole signal. The baseband which is rounded to 2 MHz is sampled at a rate of 5 Ms/s to satisfy the Nyquist criteria , and deal with the USRP clock sampling rate. This method is intended to collect all the data needed. The data is then sent via gigabit ethernet cable as jumbo packages and recorded as pure binary data files.

In this thesis the noise created by the USRP is observed and analyzed with respect to GPS signals. Statistically the USRP has a higher noise floor than other more expensive recording devices. The noise floor of the USRP is accounted for in [11] by connecting to an active (i.e. powered) antenna. Other researchers who have worked with the USRP have used extra amplifiers to get better data[11]. For the experiments done for this thesis, it was not necessary to have amplification past the initial active antenna amplification. This amplification is enough to raise the signal strength above the noise floor of the USRP.

2.2 USRP Software Interface

The software package used for this thesis is GNU Radio Companion. GNU Radio Companion's use of UHD blocks make integration with the USRP simple. An example setup of record and playback in GNU Radio Companion seen in Figure 2.2 shows the simplicity of this specific GUI.

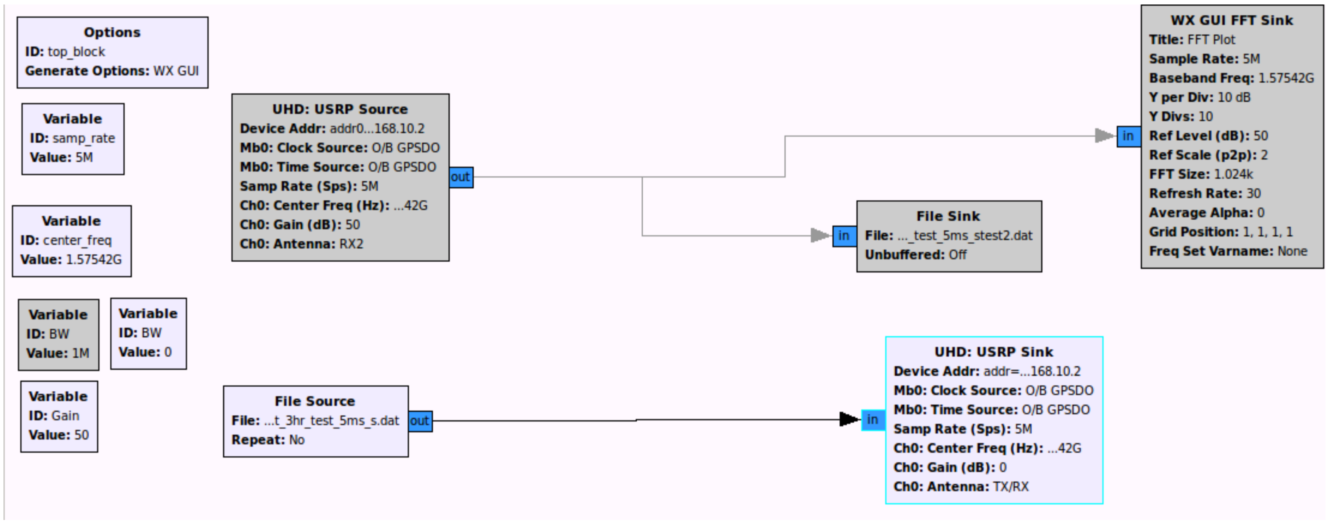

Figure 2.2: GNU Radio Companion

GNU Radio software is C++ code that is wrapped in Python to make it more easily accessible. Each block in Figure 2.2 is C++ code wrapped in python and the lines between blocks are pure python. The python is used for simplicity and the C++ code is needed to run at the faster speed. This can be run in multiple ways; it can be run in a bash script, in terminal, and in GNU Radio Companion which is the method used in this thesis.

The center frequency variable in Figure 2.2 was chosen as L1(1.57543 GHz) because it is the frequency most used with the commercial receivers. Note that the bandwidth captured is not high enough to capture both L1 and L2 simultaneously. Therefore an array of USRPs is required to record and playback L1 and L2 simultaneously. The bandwidth variable is not needed, because the WBX board does not have a band pass filter on board.

The sample rate was chosen for a variety of reasons. The baseband chosen is approximately 2 MHz to capture the entire signal. A sample rate of 4 MHz minimum is used to satisfy Nyquist. The onboard TCXO oscillates at 100 MHz and so 5 Ms/s is the sample rate chosen for simplicity. Lower sample rates are desired for a smaller file sizes and less dropped packets.

GNU Radio has many options for using the USRP. In Figure 2.2, the UHD : USRP Source block has multiple settings in it: one of the settings is a timing choice. Some of the timing choices include TCXO, GPSDO, MIMO, and External clock. This thesis makes use of the GPSDO which disciplines the onboard TCXO with a 10 MHz signal and PPS signal. For the tests using the CSAC, the clock is connected to the external SMA ports, and the external option is chosen from a pull down menu in the UHD: USRP Source block. Finally, the MIMO option connects two USRP's together synchronizing their clocks and allows the transfer of IF data over one Ethernet cable.

A Software receiver was also used during data collection. The software receiver used for this thesis is GNSS-SDR. This is an open source version of a GPS receiver that will take a binary file from the USRP and give position solutions. GNSS-SDR is used to observe the effects of USRP playback on a GPS signal. The software receiver uses base blocks from GNU Radio as an interface to the USRP and provides computed GPS position solutions.

A software defined receiver works with the base principles of GPS. For this specific receiver the data file type needs to be specified (i.e. data format short, complex, real etc). The sample rate and requested outputs have to be input to the software receivers. The software then takes the binary data in the file chosen, acquires GPS signals, decodes the data bits while tracking the signal, and finally calculates a position.

2.3 External Hardware/Software

The USRP is used in conjunction with multiple items. This thesis uses an active antenna for amplification in contrast to [11],which uses an inline amplifier. A low noise amplifier was tested, but was found to corrupt the signal. To get an amplifier working in line with the receiver, an ultra-low noise amplifier was tested. This amplifier also degraded the signal between 2dB-Hz and 5dB-Hz when compared to no extra amplification. Because of this degradation, no amplifier is used for this thesis.

The USRP transfers data very quickly and requires a fast and large hard drive to record properly. To satisfy this need, an external solid state drive is connected via USB 3.

This thesis relies on the synchronized capture of data. To ensure this, a powered four way splitter is used. In conjunction with this splitter, a standard Ublox 6 series and a Novatel Propak v3 are used. The Novatel is chosen because of its ability to capture data and use information from NTRIP to calculate Narrow Integer RTK solutions. These RTK solutions are to be used as truth when compared to standard GPS data. A diagram of the hardware setup is shown in Figure 3.1. The software used for the data collection for the Novatel is its proprietary software, Novatel Connect. This is a simple GUI that allows one to see the statistical data real time and capture many different outputs of the receiver. Some of the outputs include the bestpos option and GPGGA: two of the most highly used data components in this thesis. The Ublox data on the other hand uses a secondary terminal software recorder called Putty to capture its data. This allows for the capture of the NMEA (National Marine Electronics Association) messages naturally output by the Ublox receiver. For some of the testing with the Ublox the pseudoranges are recorded. This is done with GoGPS, a free piece of software that will record and output some NMEA messages as well as raw pseudorange measurements and navigation data in rinex files.

Chapter 3

USRP and GPS Receiver Static Data Research

Chapter three describes how to record and playback static data. All the static data is captured using the antennas on the roof of the Woltosz Engineering Research Laboratory at Auburn University. This chapter begins with timing solutions and how clock accuracy affects the GPS position solution. The three clock solutions that are discussed in this section are mentioned in chapter two. After comparing clocking solutions, the validity of playback repetition is confirmed in section three. Finally, lower level measurements are analyzed to narrow down where the extra error may be coming from.

3.1 Static Testing Comparison Between GPSDO and Internal USRP Clock

The first section of chapter three compares two of the three timing options. The two timing options in this section are TCXO and GPSDO. In this section, the static setup will be discussed, and the GPSDO is shown to be vastly superior to TCXO timing options.

3.1.1 Static Setup

When designing the static setup, as mentioned in chapter two, the signal has to be split three or four ways. The signal comes from a Novatel pinwheel down a 90' LMR 400 coax cable to the powered splitter. The diagram of the setup used for the multiple static datasets are shown in Figure 3.1. The Novatel, Ublox, USRP, and GPSDO(if used) are connected to each of the ports. Taking all the data from a single antenna reduces the number of variables to account for. The Novatel is used to gather the truth position by averaging a narrow integer solution captured at the same time as the other data sets. This is used in later calculations and observations.

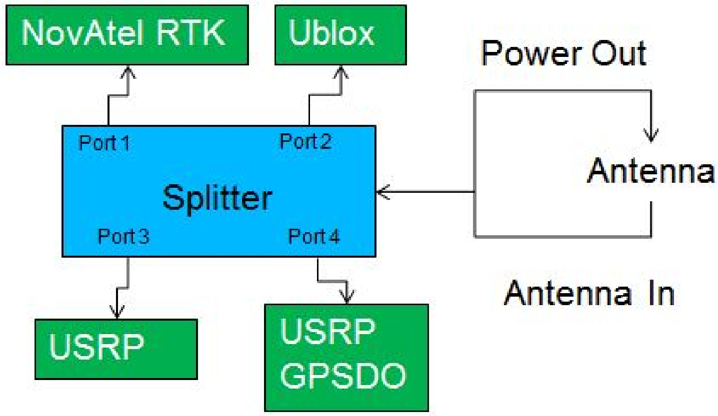

Figure 3.1: Static GPS Hardware Setup

For playback, the GPSDO has to be connected to a GPS antenna (if used) for accurate timing. The signal that is played back is then run through two 30 dBm attenuators into a Ublox receiver. Most of the data is captured with the GPSDO excluding one static test and one dynamic test section. The more accurate clocking changed the errors from 100 meters to single digit meters of error. Therefor the accurate timing was necessary to make accurate conclusions about the data that is played back.

All the static data gathered for this thesis was taken at the location shown below in Figure 3.2. The position averaged from the data is 32.605363880466456 North and -85.486936035232276 East which is used as truth.

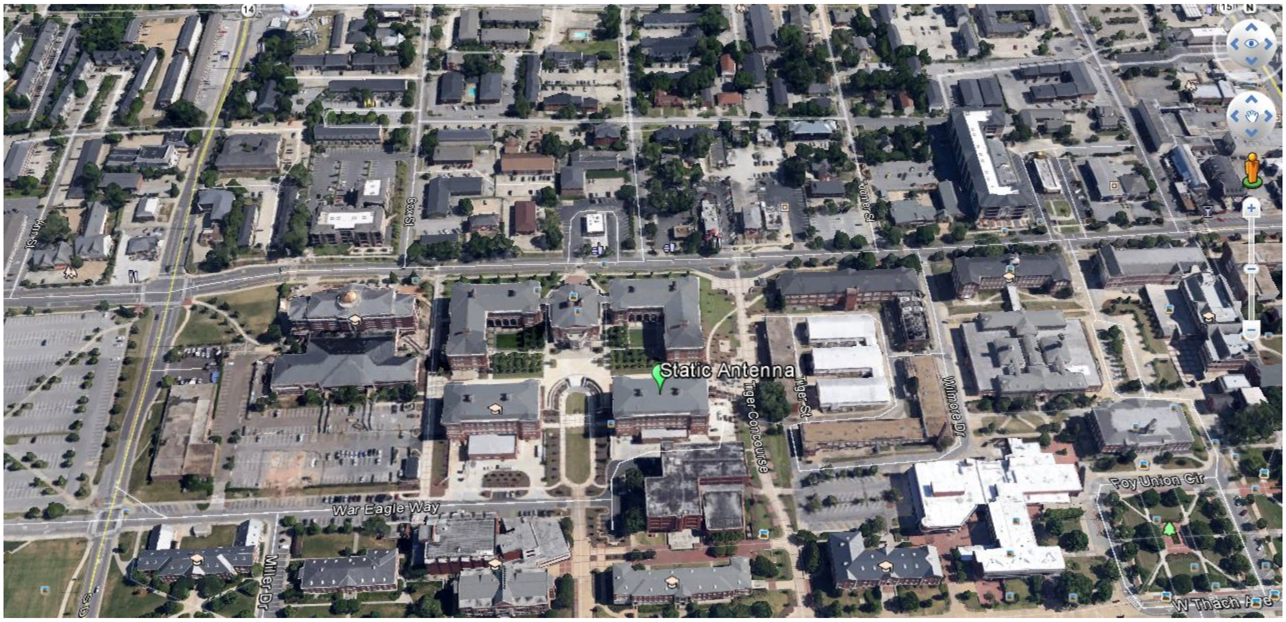

Figure 3.2: Data Collection Point for Static Position Analysis

Because the data is gathered by hand, the start time of each data run is different. For a proper comparison, the data needed to be synchronized. All the files have UTC time recorded along with the positions and therefore are parsed according to the UTC time. Each file is trimmed to start and end at the same time by hand in post process. Then a script that is written is used to make sure each iteration matches in time and position, dropping data points that do not match to keep the time synchronized. Because the static data is captured at 1Hz, there is no bridge between data rate and actual time.

3.1.2 Static Results without GPSDO

Testing without the GPSDO is done for a complete comparison of position error due to USRP clock error. While testing, it was observed that the GPS signal dropped quite often. When processing and plotting the data, seen in Figure 3.3 , the amount of error is notable. The maximum error in the north direction is 86.4 m error and the error in the east direction is 92.2 m, but the GPS receiver does not allow continuous drift away from truth. When recording without the onboard clock disciplined to the OCXO, the error is much worse.

With GPS, time is a critical component of the solutions as the difference between received and transmitted signal is vital to the position calculation.

For this static test position data is captured at 1 Hz with the Ublox receiver. Because of the inaccuracy of Ublox the clock, the played back signal may be offset slightly from the live signal. For this, USRP clock accuracy of nanoseconds is necessary. When a TCXO (that is only accurate to 2.5 ppm) is used, accurate positions will not be collected. Since GPS needs an accuracy of 0.1 ppm at minimum, the drift of the TCXO causes playback to be offset slightly from the true time. This causes the error that is seen in Figure 3.3.

The record and playback is sampled with a lower accuracy clock, but the messages on the L1 carrier are given with respect to the more accurate GPS time. The positions become askew during the record and playback functions. With the record and playback seen in Figure 3.3, part of the problem is possibly due to clock drift in the signal sampling. Now as the GPS receiver records its positions, it gets time updates, but the time updates do not take into account the massive USRP clock error.

Figure 3.3 is a graphical representation of the North and East positions, respectively. The positions from the played back data and the live data have both been subtracted from truth defined earlier; the movement away from the point at each iteration is considered the error of the receiver.

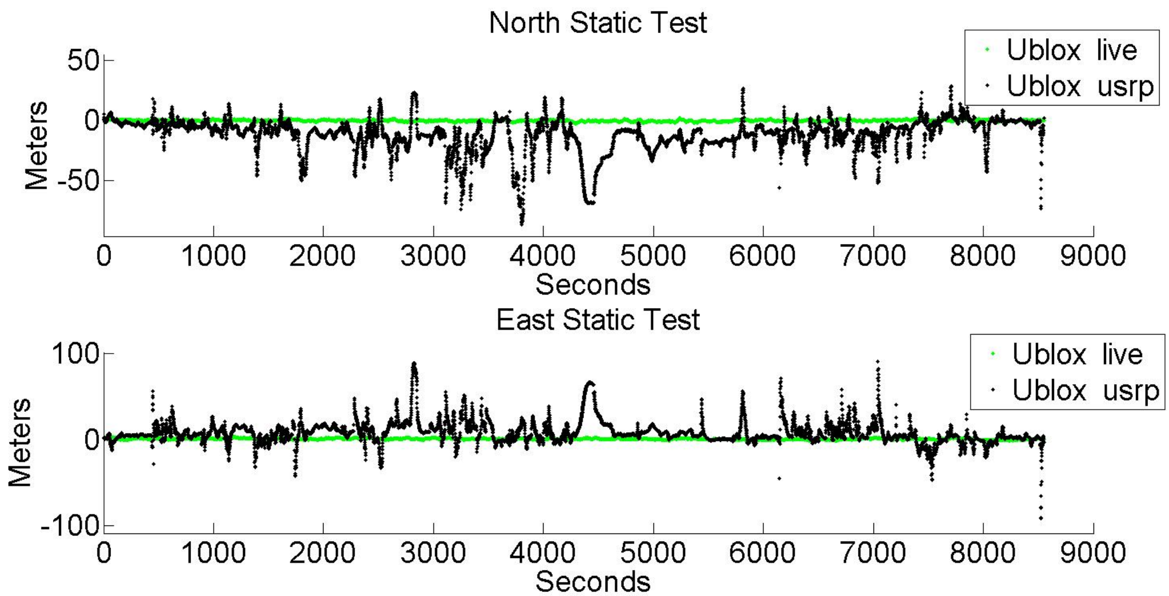

Figure 3.3: Position Differenced From Actual Position With Internal USRP Clock

In Figure 3.4 the playback and live data are differenced. The data in Figure 3.4 shows a much more accurate representation of the error caused by the USRP. There is a change in clock bias for each power cycle of the GPS receiver. The clock bias is assumed to be minimal in this thesis, so the live and played back GPS signals are handled similarly. Because the receiver handles live and played back data the same, the position solution should be the same. This assumes constant clock drift of the GPS receiver used, and therefore the clock error is differenced out.

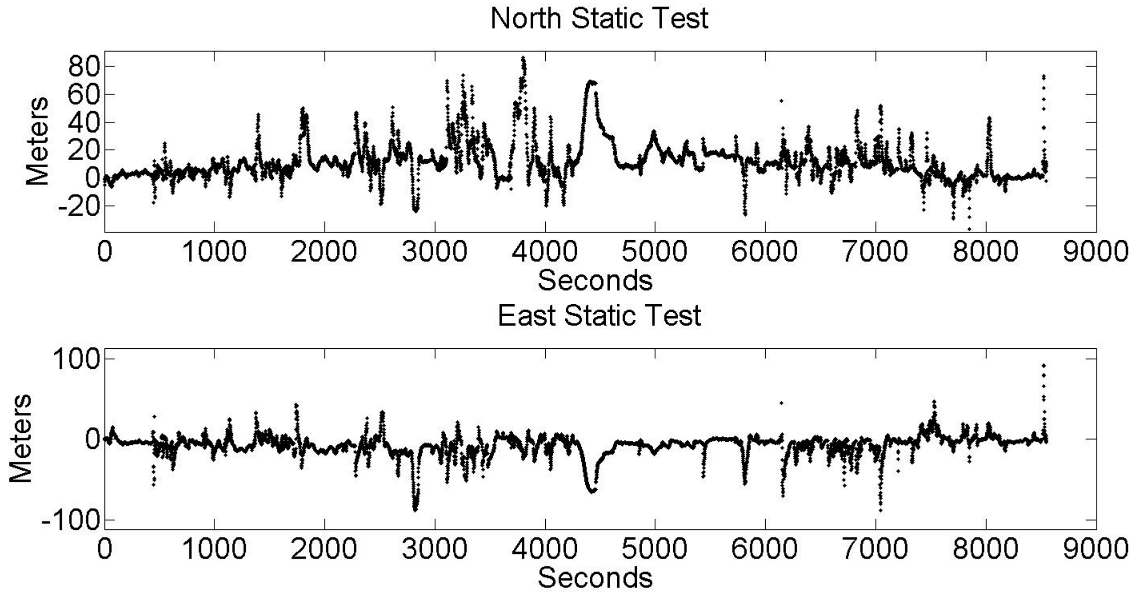

Figure 3.4: Difference Between Live and Playback Position With Internal USRP Clock

The error statistics can be seen in Table 3.1. The Ublox live data has a mean of 1.25 m and a smaller than expected standard deviation for a 2-3 hour period. In comparison to the live signal, it can be seen that without clock corrections the USRP signal is of no use. In [10] the difference in drift from an OCXO and a TCXO is shown which range from 2.6e-14 to 6.9e-13 respectively. Because GPS requires accurate timing, spikes in error are expected with a lack of clock accuracy. Also note in Table 3.1 the 2D Ublox Live - Playback is the difference between the statistical values in 2D Ublox Live and 2D Ublox Playback. The 2D Ublox Live - Playback Iteratively is statistics calculated from the data created by differencing live and playback data iteratively, as seen in Figure 3.4.

Table 3.1: 2D GPS Statistics for Static Data With Internal USRP Clock

Scenario	Mean Error (m)	Std Dev Error (m)	RMS Error (m)
2D Ublox live	1.25	0.63	1.40
2D Ublox Playback	17.91	16.87	24.60
2D Ublox Live - Playback Iteratively	12.95	13.08	18.41
2D Ublox Live - Playback	-16.66	-16.24	-23.2

In this section, it was shown that the USRP onboard TCXO is not accurate enough to allow for correct record and playback scenarios. Also note that not all the error comes from the USRP, but it is a culmination of errors that create large error statistics.

3.1.3 Static Results with GPSDO

In this section, the addition of a GPSDO is used. As mentioned earlier, the GPSDO is GPS disciplined and much more accurate than the TCXO. The GPSDO is approximately 100 times more accurate than the onboard TCXO. Because of this difference, the USRP works much better with the more accurate clock, as shown below in Figure 3.5. Though the dynamic data is revisited later without the GPSDO, one can see the increase of accuracy is needed to accurately portray the position data.

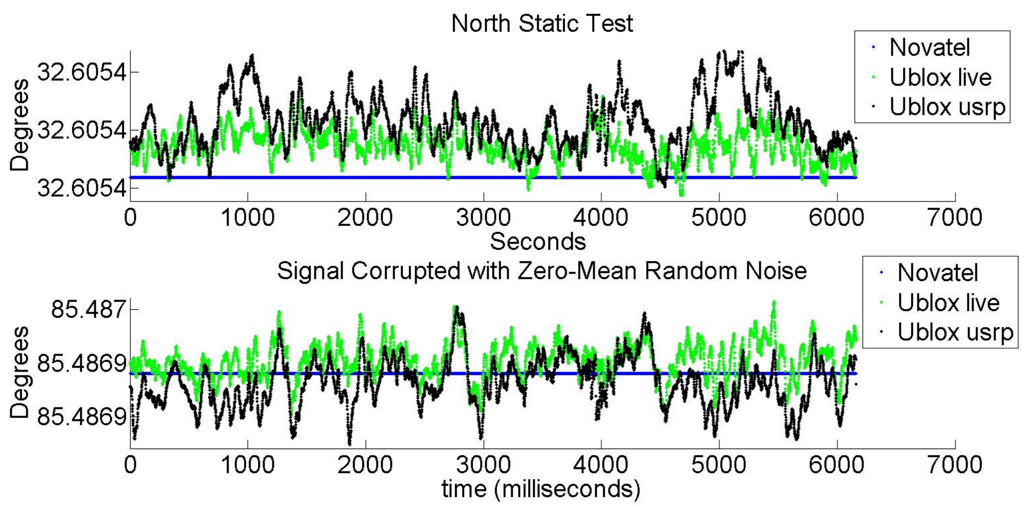

Figure 3.5: Static Test With GPSDO

The RTK position is differenced from the Ublox position and the position is converted from degrees into meters to get Figure 3.6. This conversion into meters from degrees is done with the following parameter: $1degree = 60arc/min$ $1arc/min = 1852meters$. Seen below, there is a small bias in the north and east direction. In Table 3.1, the mean error gives a good idea of how much bias there is. This bias is not purely caused by the USRP, but may include the GPS receiver clock bias.

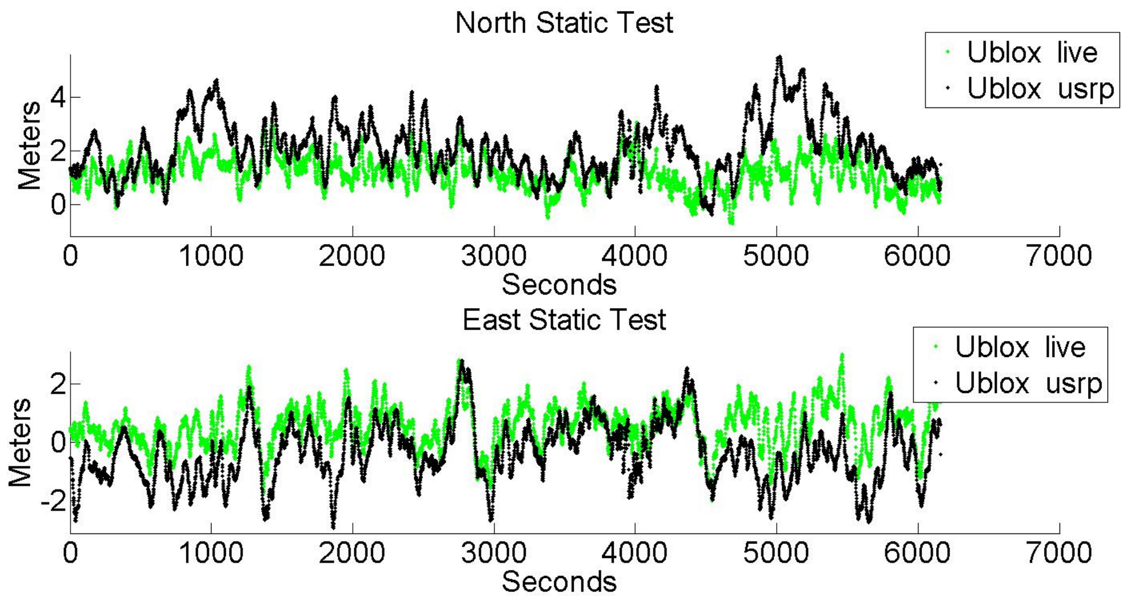

Figure 3.6: Position Differenced From Actual Position With GPSDO

The model comparison starts here with the static difference of the Ublox position and the played back Ublox position. As seen in Figure 3.7, there is approximately 6 meters of total error over all the data which is less that the Ublox or USRP separately. In the north direction, the max error is 1.6483 m and the minimum is -4.2596 m, making the overall maximum distance error of 5.9079 m. For the East, the maximum error is 3.1854 m and the minimum is -1.2408 m making the other over all distance for total maximum error 4.4263 m. As is shown by geometry, the total maximum error can be calculated using the Equation 3.1 and gives a normalized maximum error of 7.3821 m for the latitude and longitude directions added by the USRP.

$$\Delta xy = \sqrt{\Delta x^2 + \Delta y^2} \tag{3.1}$$

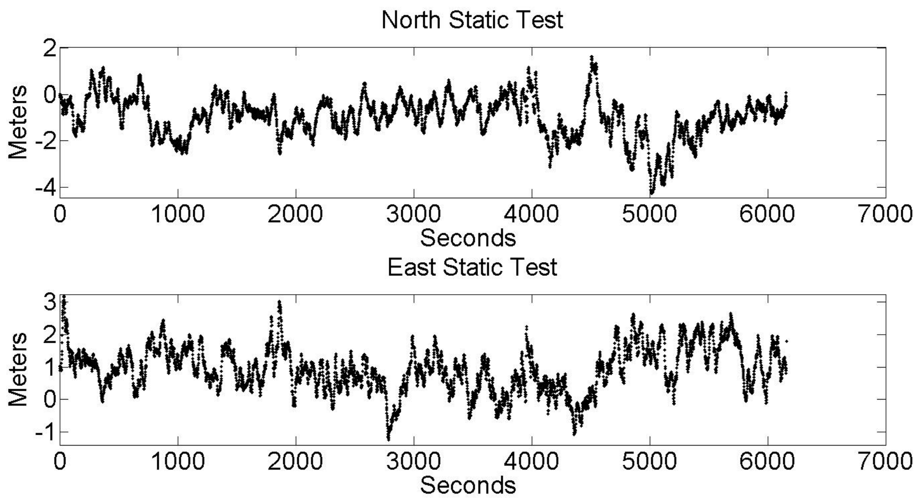

Figure 3.7: Difference Between Live and Playback Position With GPSDO

In an attempt to look for specific frequencies and other patterns in the error, the spectral density was taken of the data. One thing that is observable between the recorded and played back data, is the drop in power during playback of approximately 4dB/rad/s. There were no other differences noticed in the spectral content are the errors as shown in Figure 3.8.

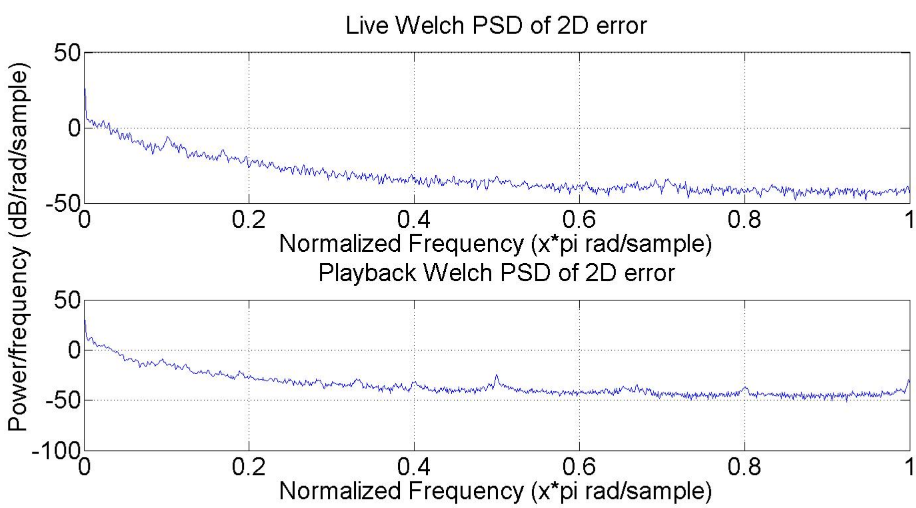

Figure 3.8: Static Live vs Playback PSD of Position

During the test with the GPSDO, the carrier to noise ratio measurements were captured. These measurements are a good guide for the strength of GPS signal from individual satellites. The lower the carrier to noise ratio is, the worse the signal is overall. The carrier to noise is slightly different between live and playback, seen in Figure 3.9. To get a better look at the changes caused by the USRP, the live and played back carrier to noise signals are differenced and shown in Figure 3.10. These tables show that when clocking is accurate enough the signal is not heavily degraded.

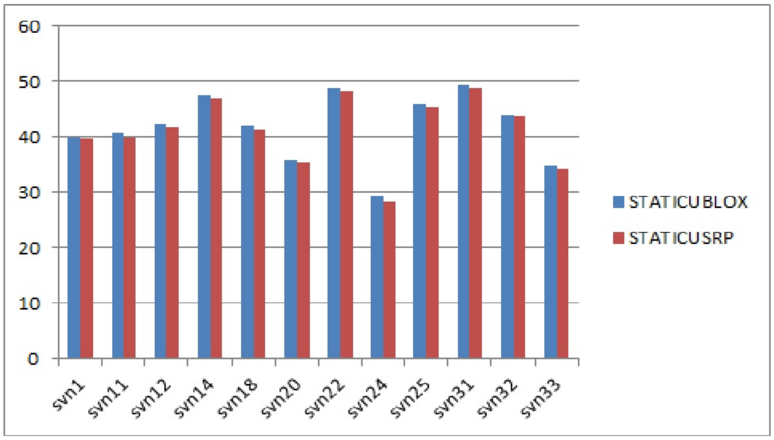

Figure 3.9: Comparison of C/No with GPSDO with GPS

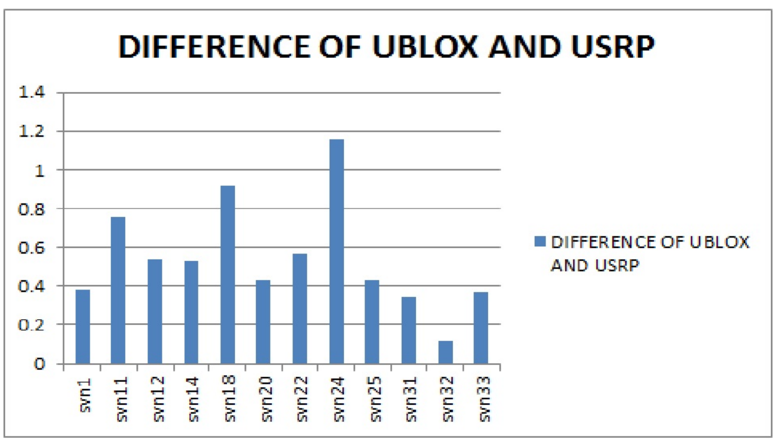

Figure 3.10: Differenced of C/No with GPSDO with GPS

3.1.4 Statistics with GPSDO

In this section, the statistics of the data collected and played back using the GPSDO will be discussed. The main statistics calculated from this data are shown in the two tables below. Table 3.2 is a table of the statistics calculated on latitude and longitude individually. Altitude is not used in this thesis, because the height error is least important when dealing with ground vehicles. As can be seen, the USRP does add error to the position solutions, but it is at a magnitude that does not invalidate the data that is played back.

Table 3.2: Latitude and Longitude GPS Statistics for Static Data with GPSDO

Scenario	Mean Error (m)	Std Dev Error (m)	RMS Error (m)
Lat Ublox live	1.16	.61	1.32
Lat Ublox Playback	2.12	1.07	2.37
Lat Ublox Live-Playback Iteratively	-0.96	0.88	1.30
Long Ublox live	.56	.76	.95
Long Ublox Playback	-.38	1.05	1.08
Long Ublox Live-Playback Iteratively	0.94	0.70	1.18

Because latitude and longitude are considered the most important measurement in this study, below is a table of this 2D statistical analysis. When looking at the two dimensional statistics it is easier to get a more cumulative idea of the errors. In Table 3.3 it can be seen that the mean is not zero for the Ublox and USRP difference. The standard deviation and RMS error does increase, but both increase less than 1 meter. This is less than 1/3 of the overall error of GPS.

Table 3.3: 2D GPS Statistics for Static Data with GPSDO

2D Scenario	Mean Error (m)	Std Dev Error (m)	RMS Error (m)
Ublox live	1.53	0.54	1.62
Ublox Playback	2.39	1.05	2.61
Ublox Live-Playback Iteratively	1.05	0.77	1.30
Ublox Live-Playback	-.86	-.51	-.99

3.1.5 Static Conclusions with and without GPSDO

It is clear from the static data that a GPSDO is required to get acceptable data for USRP playback. The error itself comes from two different sources between the live and played back data. The error comes from both the USRP and the Ublox receiver for the played back data. The USRP inserts noise during the process of record and playback from its high noise floor and the clock error. In addition to the USRP adding error during record, it does the same during playback. There is also error from the Ublox receiver clock, and even though it is the same data processed the same way by the same receiver, the clock drift still exists and changes the position error.

3.2 CSAC Timing

3.2.1 Background

In Section 3.1 the basic need of accurate timing for the USRP was discussed. Thus far, two methods of timing have been used. The first method was using a TCXO, this is very inaccurate and the error was shown to be unacceptable. The GPSDO was then used, and the standard deviations decreased from 20m to 2m. The third method, timing with the CSAC, will be discussed in this section.

3.2.2 Hardware Setup

When setting up the CSAC, a few changes are needed. First, the USRP cannot have a GPSDO attached to it internally; if it does the GPSDO will take precedence and the USRP will not use the external clock reference. Second, the CSAC needs to output both a 10 MHz clock signal and a 1 PPS signal. The 10 MHz signal disciplines the on board TCXO and the PPS tells the USRP when to start the data collection. The CSAC requires about 15 minutes to stabilize [1], so for this test the CSAC is turned on 15 minutes prior to any data recording. The whole USRP setup can be seen in Figure 3.11.

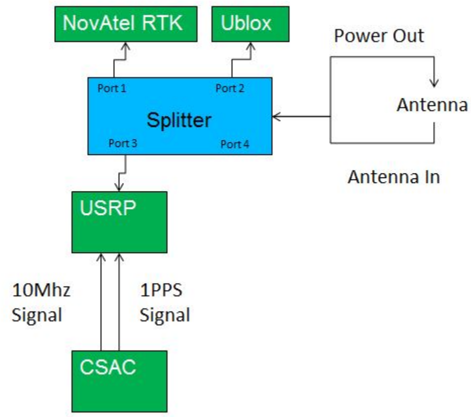

Figure 3.11: Static Hardware Setup with CSAC

3.2.3 Results

Because the USRP with the GPSDO has timing that is disciplined by GPS, the CSAC playback is expected to perform about the same as the data taken with the GPSDO. As is seen in Figure 3.12, the playback data of the Live and playback Ublox and Novatel RTK, looks much closer to the live Ublox than in Figure 3.5. After the first 500 seconds, the positions settle and are almost plotted right on top of each other.

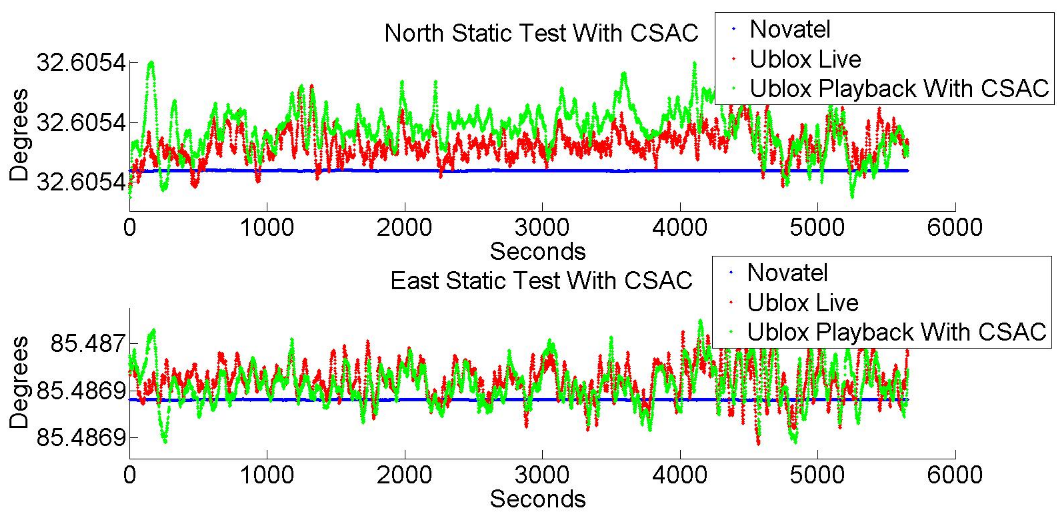

Figure 3.12: North and East Position with CSAC

Because of the position change seen in Figure 3.12, the data run is split into a start and finish section. During the live data set, the Ublox is running approximately 10 minutes before the data collection was started. On the other hand the GPS receiver starts providing position solutions as soon as playback starts creating the settling period seen in Figure 3.13. This settling period was visually determined to be finished at 500 seconds as seen in Figure 3.13. Because the receiver is starting from a cold start, the filters have to converge to the best position possible, and this happens around second 500. Because of the time the position takes to settle, the USRP should not be used for extremely short datasets.

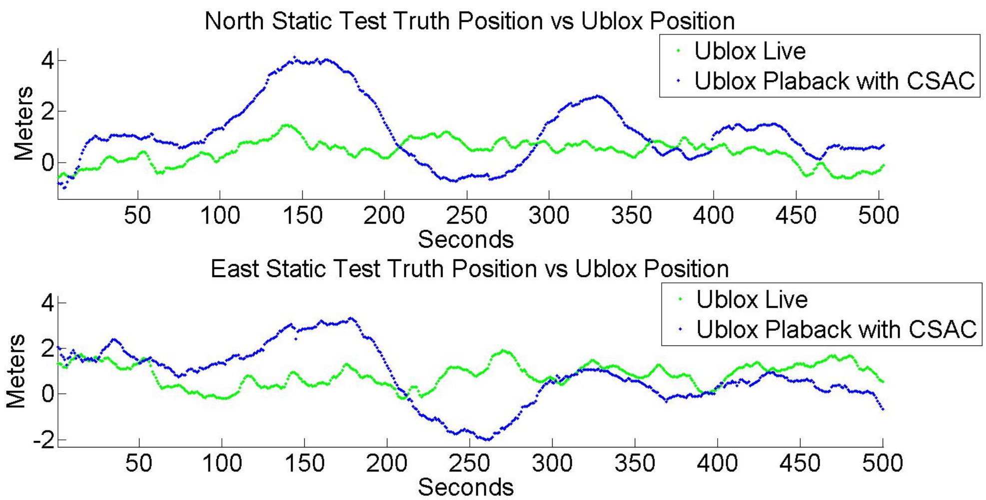

Figure 3.13: First 500 Seconds of Playback with CSAC

The position differenced from the known position continues in Figure 3.14 and shows how close the two data sets are. The separation between both data sets is much smaller than in Figure 3.6, graphically showing the improvement caused by the CSAC.

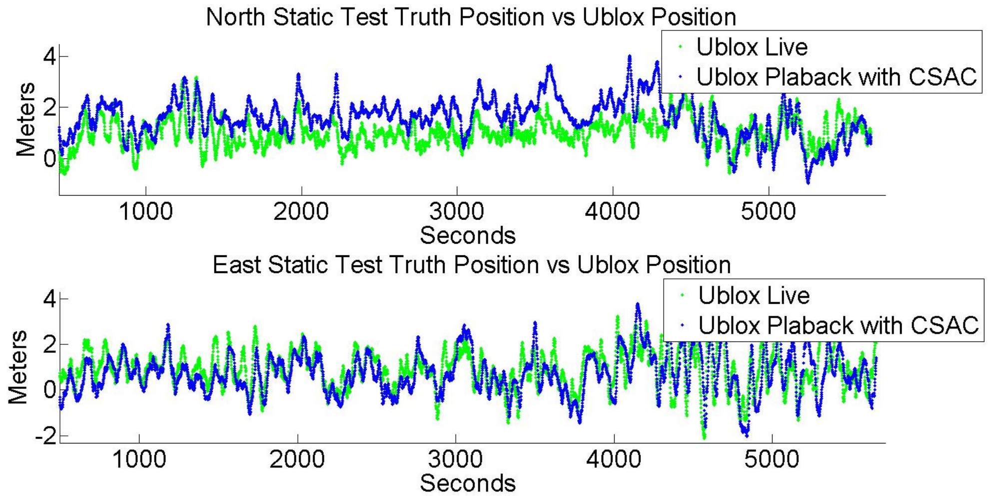

Figure 3.14: After First 500 Seconds of Playback with CSAC

The live and played back datasets are differenced again in Figure 3.15. In this figure, the bias is quite more significant than the noise. This error would not be characterized as a random walk, but is instead closer to a bias with white noise.

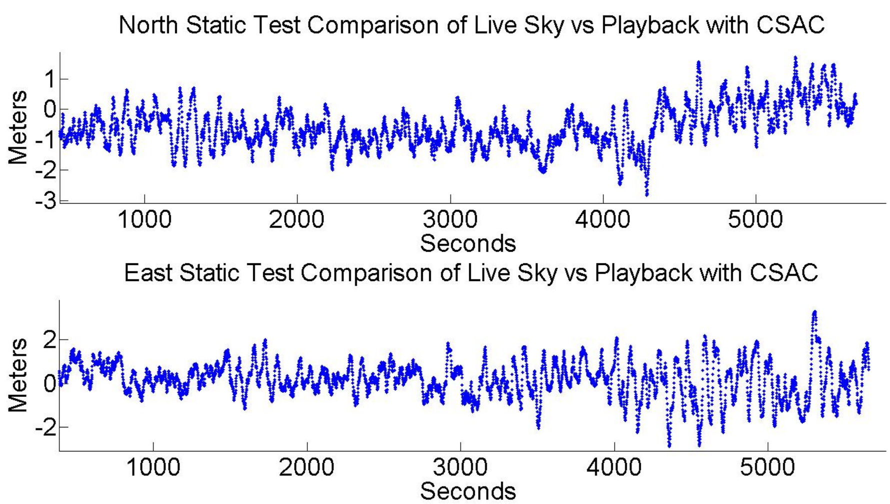

Figure 3.15: Live and Playback Differenced with CSAC

The PSD of the CSAC data is not much different from the static data with the GPSDO. Again in Figure 3.16, there are no additional frequencies added just like in the static data with the GPSDO.

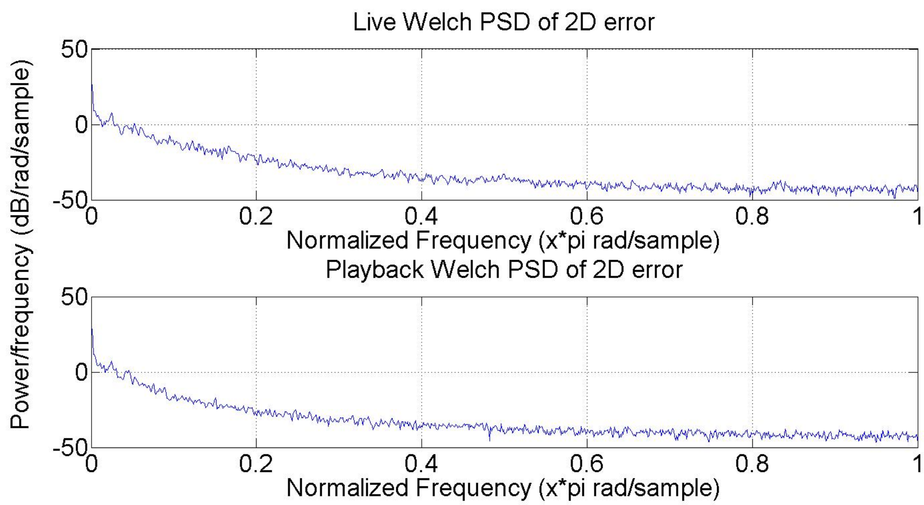

Figure 3.16: Live vs Playback PSD of Position with CSAC

3.2.4 Statistics

The statistics of the CSAC data are given in Table 3.4. There is still a bias, but the standard deviation is relatively small when looking at the difference between live and playback data. The statistics using the CSAC are better than the statistics using the GPSDO. The increased accuracy caused by the CSAC was not expected because the accuracy of the GPSDO is GPS disciplined. The CSAC is most likely more accurate because of the compounding of clock errors with record and playback.

Table 3.4: CSAC Record and Playback Data

Scenario (2D)	Mean Error (m)	Std Dev Error (m)	RMS Error (m)
Ublox live	1.60	.65	1.73
Ublox Playback	2.02	.72	2.14
Ublox Live-Playback Iteratively	-.42	0.72	.83
Ublox Live-Playback	-.42	-.07	-.41

3.2.5 Conclusions

As can be seen from the data after an initial settling period; the live and playback data are similar. In Table 3.5, the CSAC and standard GPSDO error are compared.

Table 3.5: CSAC Compared to Static with GPSDO

Scenario	Mean Error (m)	Std Dev Error (m)	RMS Error (m)
2D Ublox Live-Playback CSAC	-.42	-.07	-.41
2D Ublox Live-Playback GPSDO	-.86	-.51	-.99
CSAC-GPSDO	.44	.44	.58

The standard deviation and RMS errors show that the CSAC recorded positions have significantly better position solutions. These statistics both show the CSAC to be far superior when logging data. The CSAC has much lower clock drift and is more accurate than the GPSDO with the GPS time updates. The CSAC is more difficult to use, but from these tests it is worth it to use the CSAC over other clocking methods.

3.3 Repeatability of Record and Playback with the USRP N210

3.3.1 GPSDO GPS vs Non-GPS

Repeatability is an important consideration when using the USRP to record and playback. If the USRP is not repeatable the testing of multiple receivers would not be a viable option. The testing plan includes playing back one data set 11 times. This was done over multiple days as the individual data sets were two hours long.

For the data run that is shown in Figure 3.17 seven out of the eleven data runs were done with the aid of GPS for the GPSDO. The other four runs were done without the aid of GPS. The four runs without GPS were done to see the significance of GPS disciplined clock. In Figure 3.17 the left top and bottom data runs are the ones recorded with the aid of GPS, while on the right top and bottom are the data runs without GPS aided timing. As can be seen the data without the GPS aided timing drifted significantly.

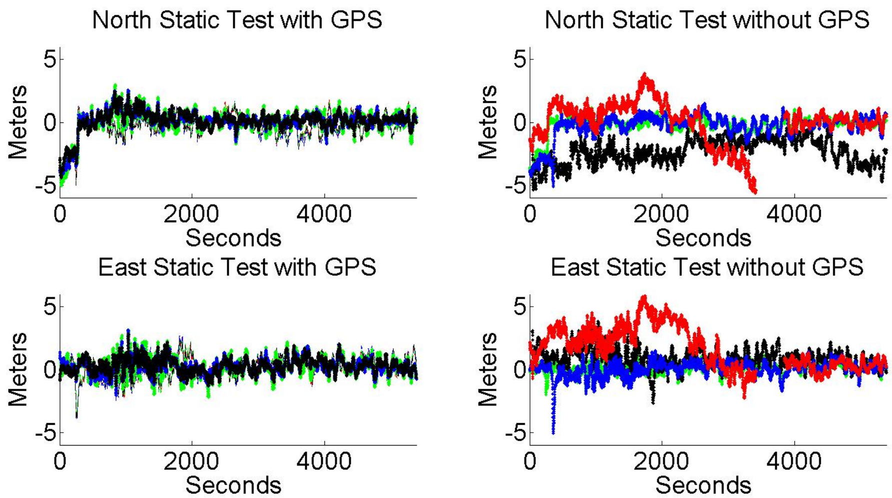

Figure 3.17: Repeatability Test With and Without GPS Aided GPSDO Timing

3.3.2 Repeatability Differences

After recording the first data sets more evaluation was required. In this section a better comparison is made between each playback cycle. For this differencing test, the first four runs of the previous test were used. Figure 3.18 show plots differencing the first four runs from Figure 3.17. This is to see the difference in error between each playback dataset. In Figure 3.18 the two plots on the left are the first Ublox data structure differenced from the other three. The plots on the right are the rest of the data differenced from each other. From these graphs the difference between each run can be observed, but a clearer picture can be seen with the calculated statistics.

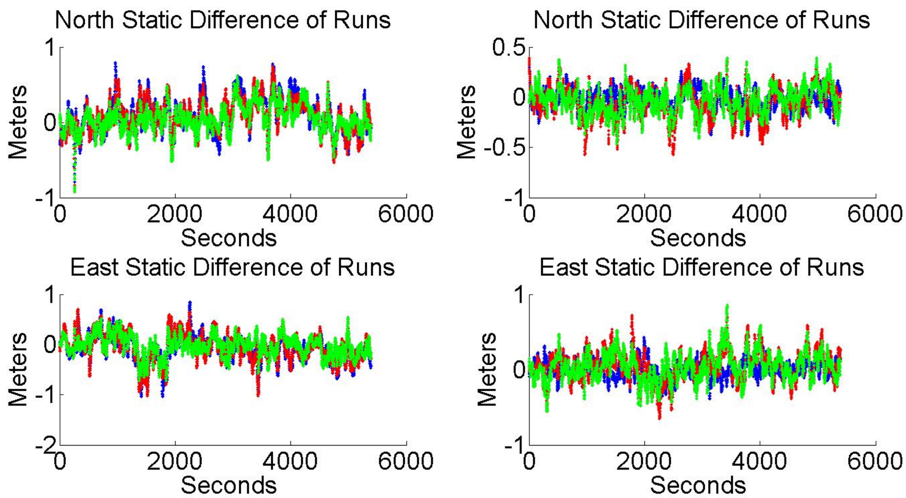

Figure 3.18: Repeatability Test Differenced

3.3.3 Statistics

The statistics from the repeatability test in Figure 3.18 are shown below in Table 3.6. These calculations are of the normalized latitude and longitude, and therefore are the two dimensional data from the difference between the runs.

Table 3.6: Error Statistics for Repeatability

Scenario	Mean Error (m)	Std Dev Error (m)	RMS Error (m)
Live	1.18	0.61	1.33
Playback 1	1.63	0.94	1.88
Playback 2	1.59	0.94	1.84
Playback 3	1.60	0.95	1.86
Playback 4	1.59	0.93	1.85
Playback 1-2	0.041	0.003	0.037
Playback 1-3	0.030	-0.002	0.025
Playback 1-4	0.036	0.010	0.036
Playback 2-3	-0.011	-0.006	-0.012
Playback 2-4	-0.005	0.007	-0.001
Playback 3-4	0.006	0.011	0.011
Playback 1-2 Iteratively	0.33	0.18	0.38
Playback 1-3 Iteratively	0.31	0.18	0.36
Playback 1-4 Iteratively	0.24	0.15	0.28
Playback 2-3 Iteratively	0.14	0.08	0.16
Playback 2-4 Iteratively	0.22	0.13	0.26
Playback 3-4 Iteratively	0.20	0.12	0.23

3.3.4 Repeatability Between Receivers

One of the goals of writing this thesis is to show how the data from the USRP can be used to evaluate different receivers. To do this, two completely different types of receivers are compared in both live and playback scenarios to show whether the testing is repeatable in comparing receivers. The two receivers chosen for their separate methods of signal processing, were the Ublox EVK 6T and the Novatel OEM V3. While running this test a higher sample rate of 10Ms/s was required compared to the 5Ms/s used in the rest of the paper. This was to satisfy the Novatel receiver requiring a higher quality signal.

3.3.4.1 Results

The played back signal is run from the USRP through a splitter to both Ublox and Novatel receivers. The Novatel GPGGA measurements are compared to the Ublox data in Figure 3.19. Different receivers react differently to errors and this test will show how these two receivers react to the errors created by the USRP. It can be seen in Figure 3.19, that the Novatel filters the data much more than the Ublox receiver, and this shows that the errors created by the USRP do not have the same effect on the Novatel as on the Ublox.

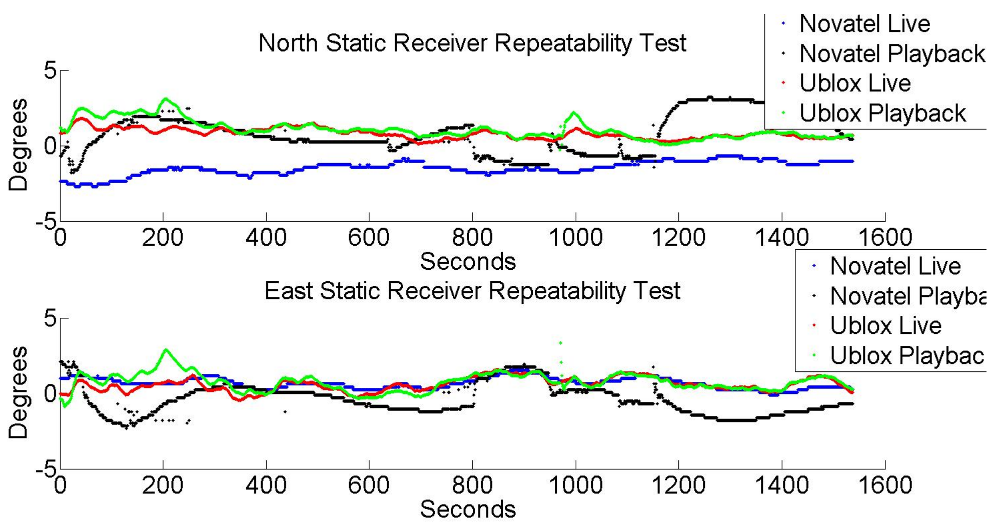

Figure 3.19: Repeatability Test Differenced

From this data the statistics below in Table 3.7 is extracted. With this specific data set, the Novatel did not calculate a better position than the Ublox. However, the USRP playback signal did effect both receivers in approximately the same way.

Table 3.7: 2D GPS Statistics for Static Data with GPSDO

2D Scenario	Mean Error (m)	Std Dev Error (m)	RMS Error (m)
Ublox live	1.09	.33	1.1
Ublox Playback	1.39	.68	1.55
Novatel Live	1.65	.49	1.72
Novatel Playback	1.58	.96	1.85

3.3.5 Conclusions

In this section the repeatability of the USRP was discussed with a standard GPSDO, which can be purchased with the USRP. For this testing a few conclusions can be made. First, the USRP must have GPS data sent to the GPSDO for accurate playback. Record and playback can be accomplished without GPS-aided GPSDO, but the data is slightly more accurate when using GPS aided timing. The difference between the playback data sets are quite small, making them very repeatable. Overall, this test shows the viability of the USRP for playing back the same data multiple times. While testing the cross platform uses of the USRP, the data shows that the extra errors created by the USRP affects different receivers in approximately the same way with slight differences. This means that different receivers can be tested from one data set using the USRP.

3.4 Pseudorange and Lower Level Measurements

In this section, the pseudorange measurements are analyzed. Errors on these measurements have a direct correlation to the error in position. This section will statistically analyze the errors on pseudorange, doppler, and C/No measurements.

3.4.1 Background Work

The pseudorange is the range between satellite and with additional errors. In the pseudoranges, there are inherent errors shown in Equation (3.2).

$$\rho = r + cdt_r + +e_A + cdt_{USRP} + \sigma_{USRP} + \sigma \tag{3.2}$$

In this equation, r is the absolute range between satellite and user, e_A is the atmospheric error including troposphere and ionosphere, cdt_e is the receiver clock error, σ_{USRP} is the thermal noise error caused by the USRP, cdt_{USRP} is the clock error created by the USRP, and σ is the rest of the errors including the satellite clock error, white noise and other small errors.

The GoGPS software mentioned earlier, takes raw messages from the Ublox receiver and outputs multiple rinex files which can be processed later to gather pseudoranges, doppler, C/No, ephemeris, and more.

This section seeks to discover if during the two runs the same pseudorange data is being received during record and playback. Because the USRP records IF data at such a high rate, theoretically there should be minimal changes in the pseudoranges from record and playback through the USRP. Therefore only a minimal amount of error is expected between pseudorange lengths. According to the results, however, this is not the case.

3.4.2 Results

The first measurement type observed is the pseudorange. In Figure 3.20 the pseudoranges from live data are compared to playback. This figure verifies that good pseudorange data has been recorded for this data set (by showing there are no extreme measurement changes).

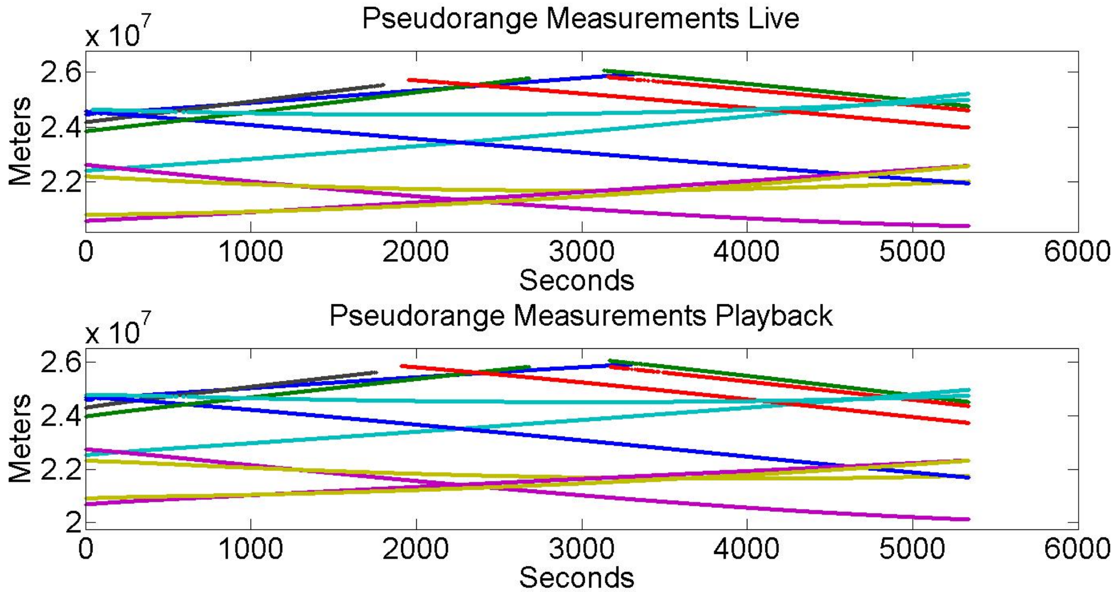

Figure 3.20: Pseudorange Measurements Live and Playback

To start looking at the changes between the recorded and played back data the time vectors are synchronized and the ranges are differenced. Each live satellite is differenced from its respective playback satellite. This is done and the result are shown in Figure 3.21, where the overall change in meters is extremely large. The error for each pseudorange measurement is extremely large expressing a possible large clock error term in the calculations. When observing the data points at one specific time; the measurements do not have a large change between pseudoranges. The error between pseudoranges at one time stamp can be seen in Figure 3.22 showing the measurement for each satellite at this time stamp. Figure 3.22 is the same plot as 3.21 zoomed into one specific point with a legend. The maximum difference between these measurements is two meters.

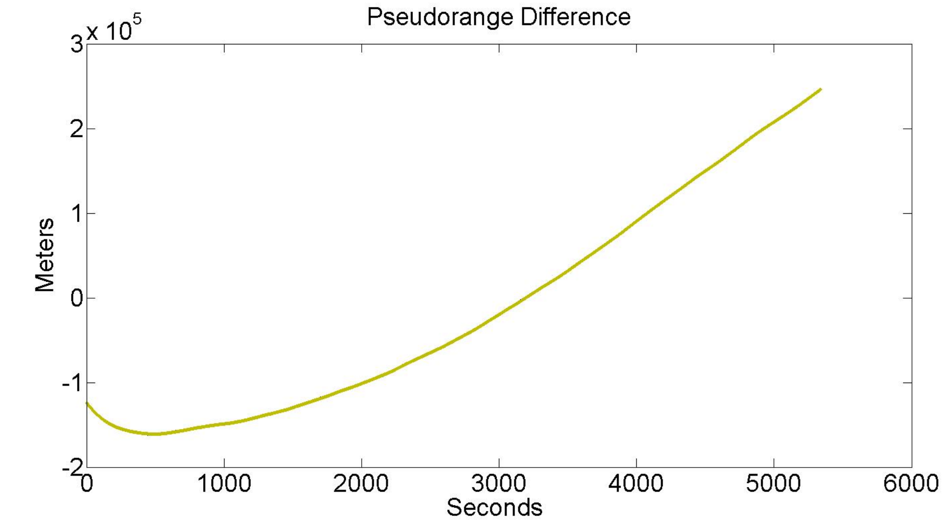

Figure 3.21: All Pseudoranges Differenced 13SVs

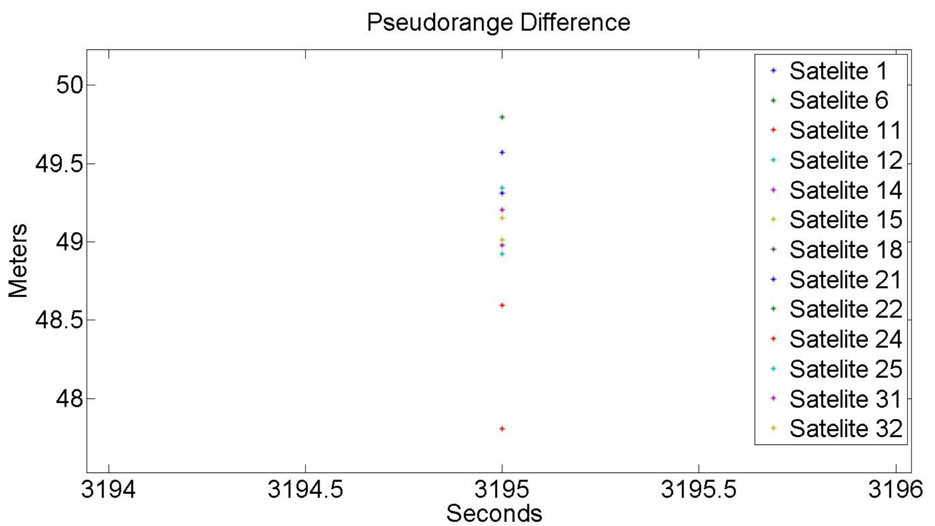

Figure 3.22: Enhanced Difference Between Pseudorange Measurements 13SVs

Figure 3.23 is a comparison of two satellites chosen for their longevity. These two satellites are both in the complete data set. Looking at the two satellites separately gives a much better idea of what error is being created by the USRP. The ranges are differenced with respect to time in the graphs on the right of Figure 3.23. This is done to see the change in pseudorange between each measurement which shows the position change of the individual satellite. In both differenced pseudorange files, the pseudoranges have a constant change in position from the live data. On the other hand, the playback data always starts offset and drifts quickly to the live pseudorange, but the change in pseudorange does not drift at the same rate and is noisy. The statistical values are provided in Section 3.4.3, but from the Figure 3.23, the extra noise is clearly seen.

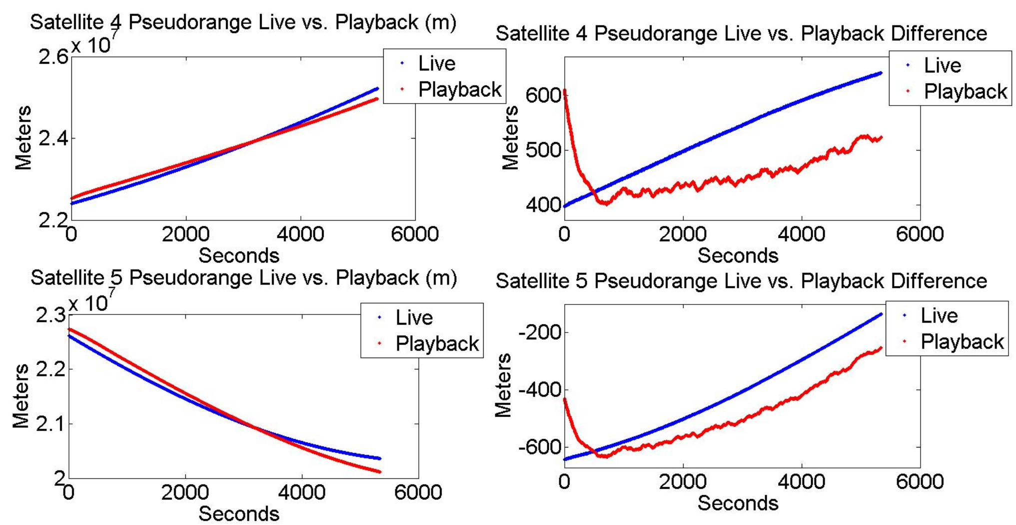

Figure 3.23: Pseudorange to Live Vs Playback

Figure 3.24 is a figure of the raw doppler measurements during this run. Right from the start there is a clear difference in the the doppler measurements from the live and played back signals. The doppler clearly has more noise and an initial offset caused by this noise.

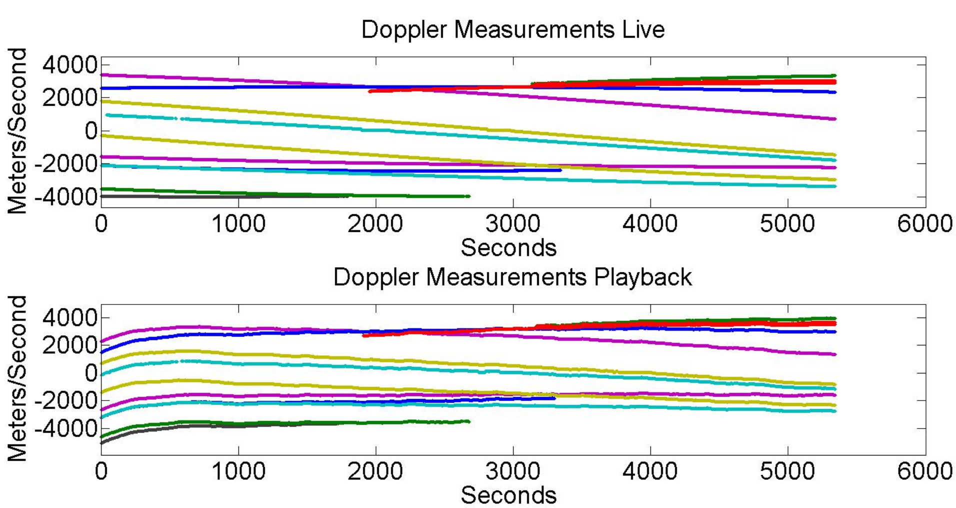

Figure 3.24: Raw Doppler Measurements

The doppler is then differenced, and just like the pseudoranges. The doppler shows a large change in magnitude of meters per second. Figure 3.25 uses the same differencing method used for the pseudorange measurements. As can be seen, there is a large error at the start, and the measurements are very noisy. This demonstrates that the same error source effects in the pseudoranges is also effect the doppler.

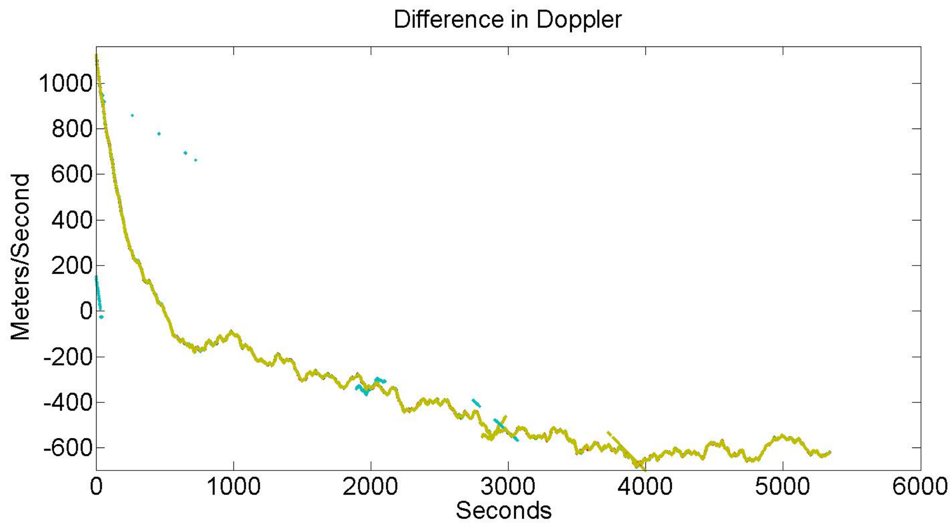

Figure 3.25: All Differenced Doppler Measurements

As shown earlier in the pseudorange section, satellites four and five are singled out for their continuous data. The doppler measurements on satellites four and five are significantly different between the live and playback data. The noise and drift of the playback data is significantly different between the two measurements seen in Figure 3.26. When the measurements are differenced in time, observe that the noise during playback is significantly higher. From what is seen in Figure 3.25 and 3.26, it can be concluded that the error here is clock noise. This is not quantified, but it is obvious that the error on the doppler is significantly large.

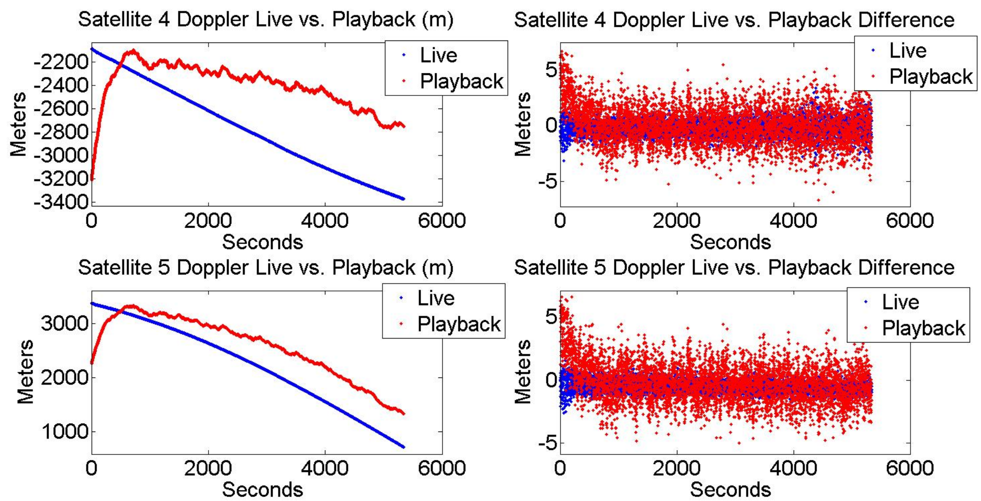

Figure 3.26: Clock Drift Observed from Differencing

Finally, to see how the carrier to noise measurements compare, they are also differenced between live and playback. This is done to observe how the carrier to noise ratios change over time. From Figure 3.27 the error is constant showing that the noise added by the USRP does not consistently change the signal power. This is a graph of the change in signal to noise measurements for each satellite, and the sparse dots are measurements that are not 1dB/Hz lower in playback.

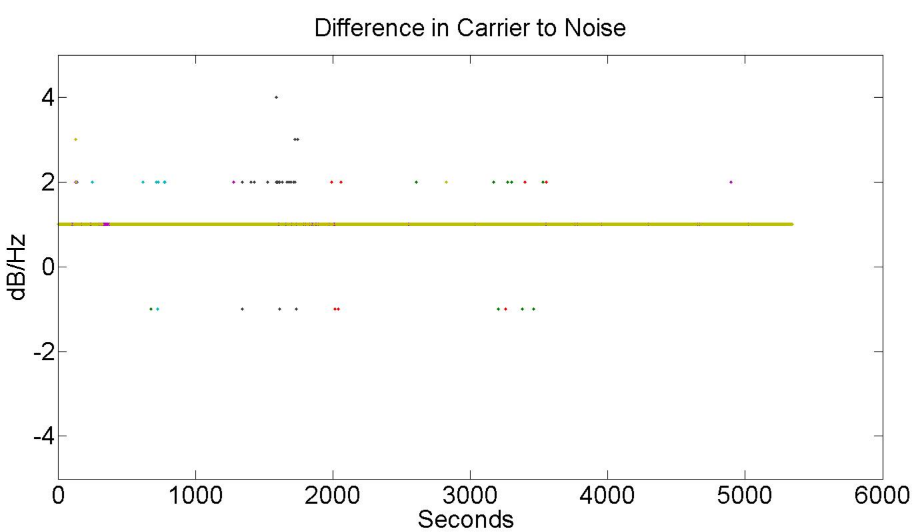

Figure 3.27: Carrier to Noise Doppler Measurements

3.4.3 Statistics

To get a more comprehensive overview of statistics, satellites four and five are used for their length and continuity. The time differenced data is used to see how the measurements change statistically over time. From Tables 3.4.3 and 3.4.3 it is easily observed, that there is a significant amount of extra error on both the pseudoranges and the doppler created by the USRP.

Table 3.8: Pseudorange Statistics

Scenario	Mean Error (m)	Std Dev Error (m)	RMS Error (m)
Satellite 4 Live	527.20	71.53	532.03
Satellite 4 Playback	-421.75	149.80	447.56
Satellite 5 Live	457.87	36.63	459.33
Satellite 5 Playback	-491.08	108.62	502.95

Table 3.9: Doppler Difference Statistics

Scenario	Mean Error (m)	Std Dev Error (m)	RMS Error (m)
Satellite 4 Live	-.24	.68	.72
Satellite 4 Playback	-.50	.43	.66
Satellite 5 Live	.08	1.69	1.70
Satellite 5 Playback	-.17	1.61	1.62

3.4.4 Conclusions

From this section the errors from the USRP have been further investigated. The USRP adds large error in position due to the low quality clock. The error seen in the pseudoranges and doppler due to the USRP recording was also seen to be very large. However the extra error seen is similar along each satellite such that good positions are calculated by the GPS receiver in playback.

Chapter 4

Dynamic Testing

In this chapter, dynamic data is gathered and discussed. This is split into three data sets: Dynamic without GPSDO, Dynamic with GPSDO, and High Dynamic with GPSDO. Both standard dynamic sets are recorded around a large circular road to keep the data as smooth as possible. The High Dynamic data set is taken on a much smaller track so that speed can be regulated allowing for much faster speeds which show higher dynamic properties of the USRP.

4.1 Data gathered

When recording the dynamic data, the hardware setup is similar to the static data. One difference between static setup and dynamic setup is the use of a mobile wireless connection for NTRIP corrections, and a stable power source. NTRIP is a piece of software that uses data from a local base station via the internet for RTK corrections. The dynamic tests also use a coax cable that is approximately 80' shorter than used for the static testing. The vehicle used for the dynamic data gathering was an Infinity G35 seen in Figure 4.2. This vehicle has no such power stability problems. The data taken for the dynamic testing is taken around the path shown in Figure 4.1.

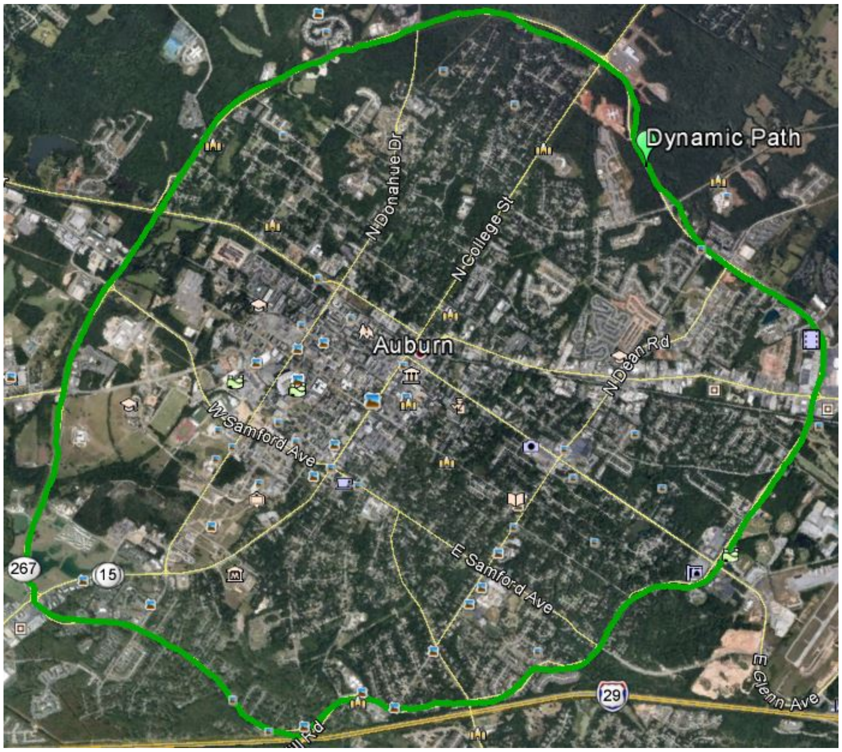

Figure 4.1: Dynamic Path

As can be seen in Figure 4.1, the data is taken on a road, and therefore standard driving practices were observed. To keep the data as uniform as possible, acceleration and deceleration is kept to a minimum.

Figure 4.2: Vehicle Used for Dynamic Test Data collection

4.1.1 Dynamic Data Analysis Using internal USRP clock

To compare to the static data, the first set of analysis for dynamic testing uses the internal USRP clock (i.e no GPSDO). This section shows the comparison of statistics between static and dynamic data using the USRP. It is observed in Figure 4.3, that the error spikes are much larger than the static data seen in Figure 3.3.

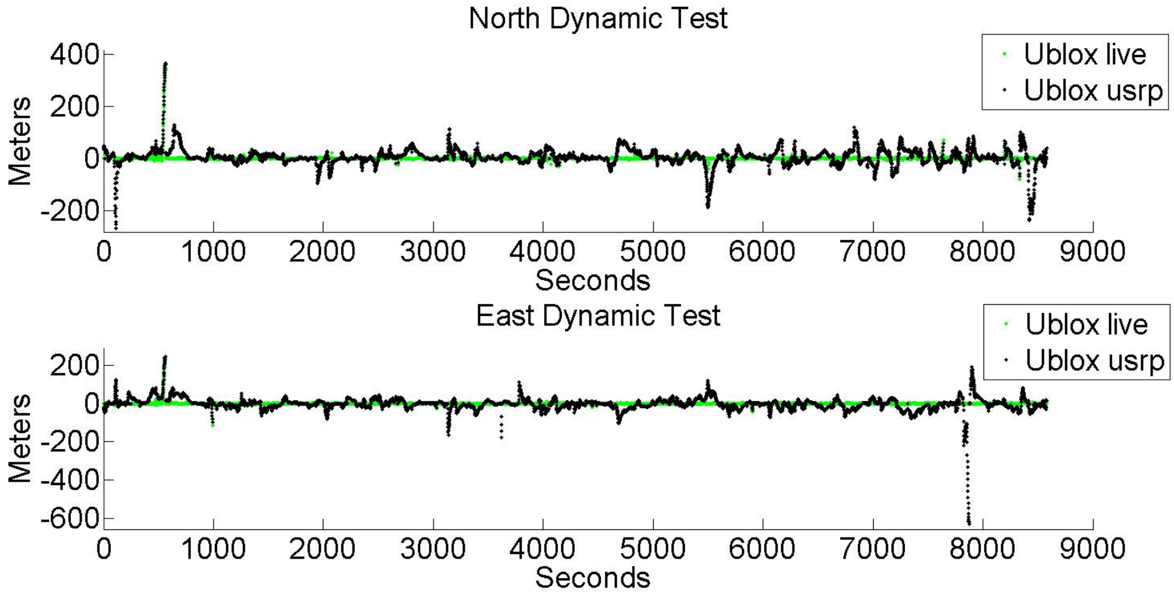

Figure 4.3: Dynamic Position Differenced From Actual Position With Internal USRP Clock

Figure 4.4 shows the amount of error the USRP adds to the dynamic signal in playback. There are multiple position spikes that are much greater than the static set. To compare static and dynamic statistics most accurately, the data is tabulated together in Table 4.1. The largest of these spikes are in Table 4.2 to quantify the magnitude of the error spikes. As seen in this table the GPS receiver reacts to dynamic and static playback data differently.

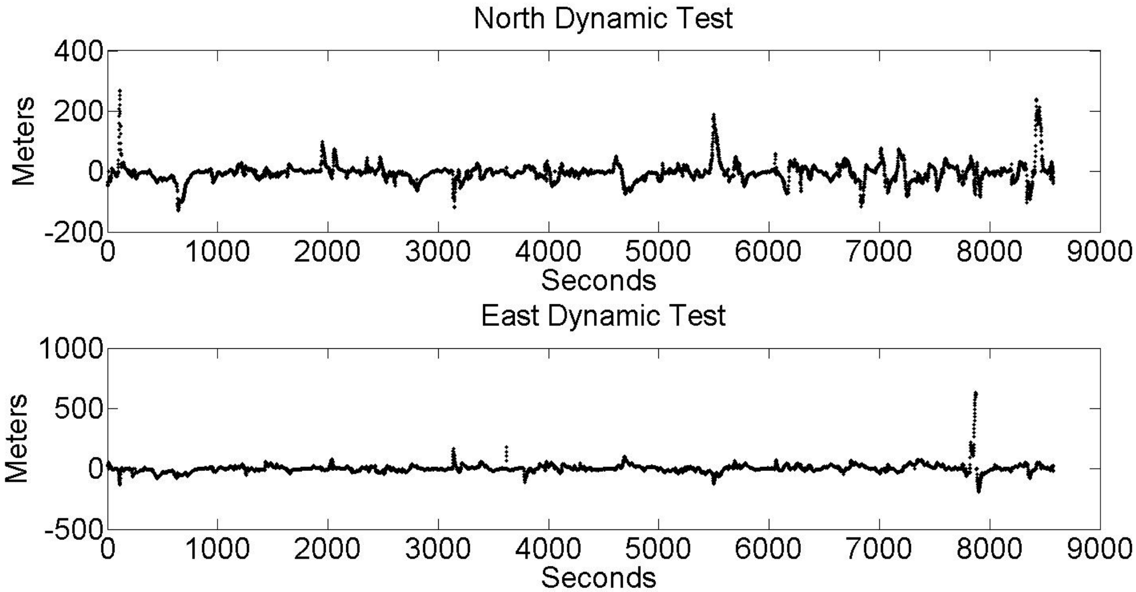

Figure 4.4: Dynamic Difference Between Live and Playback Position With Internal USRP Clock

Table 4.1: 2D GPS Statistics for Data with no GPSDO

Scenario	Mean Error (m)	Std Dev Error (m)	RMS Error (m)
2D Static Ublox live	1.53	0.54	1.62
2D Static Ublox Playback	2.39	1.05	2.61
2D Static Ublox Live-Playback	-.86	-.51	-.99
2D Dynamic Ublox live	4.87	28.04	28.46
2D Dynamic Ublox Playback	27.28	39.00	47.59
2D Dynamic Ublox Live-Playback	18.61	24.99	31.16

Table 4.2: Maximum Error Spikes Caused by USRP without GPSDO

Scenario	Position Error North (m)	Position Error East (m)
Static Data	86.4	92.2
Dynamic Data	268	631

A better understanding of the carrier to noise error can be found with the dynamic data. In the figures below the carrier to noise is averaged for each satellite shown. Figure 4.5 shows the comparison of record and playback. Figure 4.6 shows the change in C/No measurements. The carrier to noise ration changes 5.5 dB-Hz maximum and is compared to data with the GPSDO in Section 4.1.2.

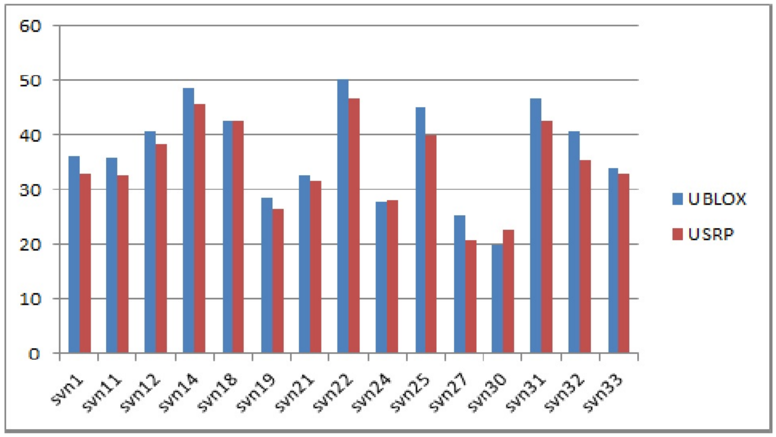

Figure 4.5: Dynamic Comparison of C/No without GPSDO

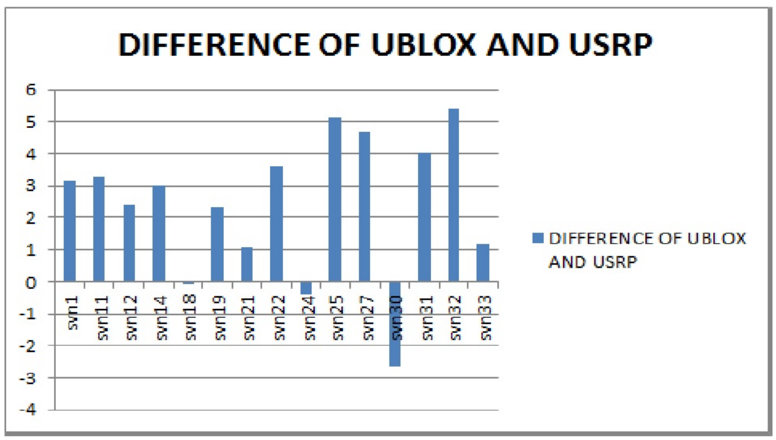

Figure 4.6: Dynamic Differenced of C/No without GPSDO

4.1.2 Dynamic Data Analysis Using GPSDO

When taking the dynamic data with the GPSDO, the only hardware change is the addition of the GPSDO. As seen in Figure 4.7 the latitude and longitude is similar to the path taken without the GPSDO.

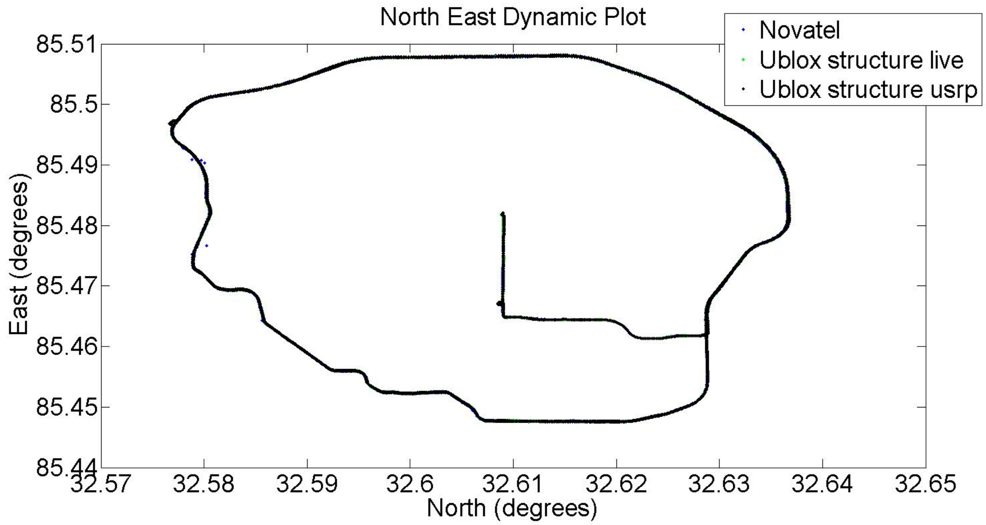

Figure 4.7: Dynamic Test With GPSDO

To get the error of the Ublox receiver the RTK position is needed for each time stamp. To run statistics on this error the Ublox data is differenced from the Novatel data seen in Figure 4.8. When the data was originally taken, the dynamic data with use of the GPSDO had large errors due to corrupted internet connection for the Novatel. Therefore these data points were removed as seen in Figure 4.8.

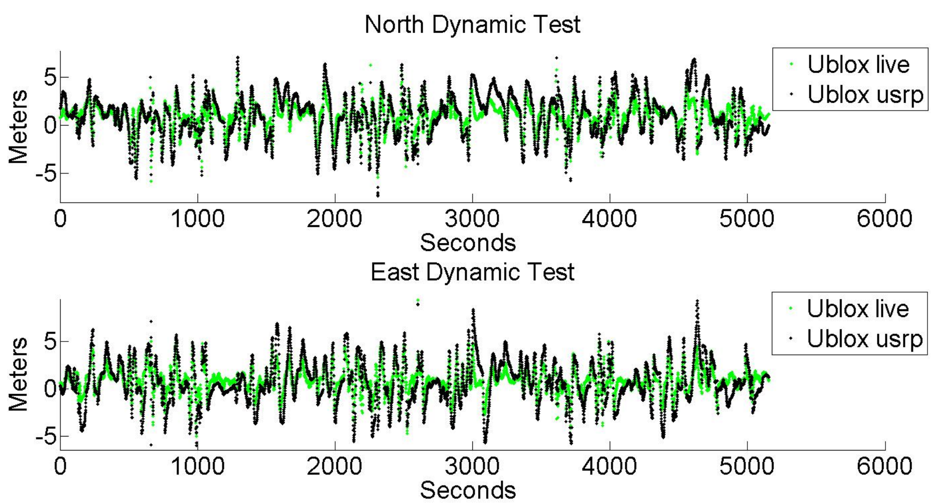

Figure 4.8: Dynamic Position Differenced From Actual Position With GPSDO

Figure 4.9 is a result of differencing live and playback for the dynamic data with the GPSDO. With a simple visual comparison between Figures 4.9 and 3.7 it can be seen that dynamics add extra error to the playback. The error statistics are provided later in Section 4.1.3.

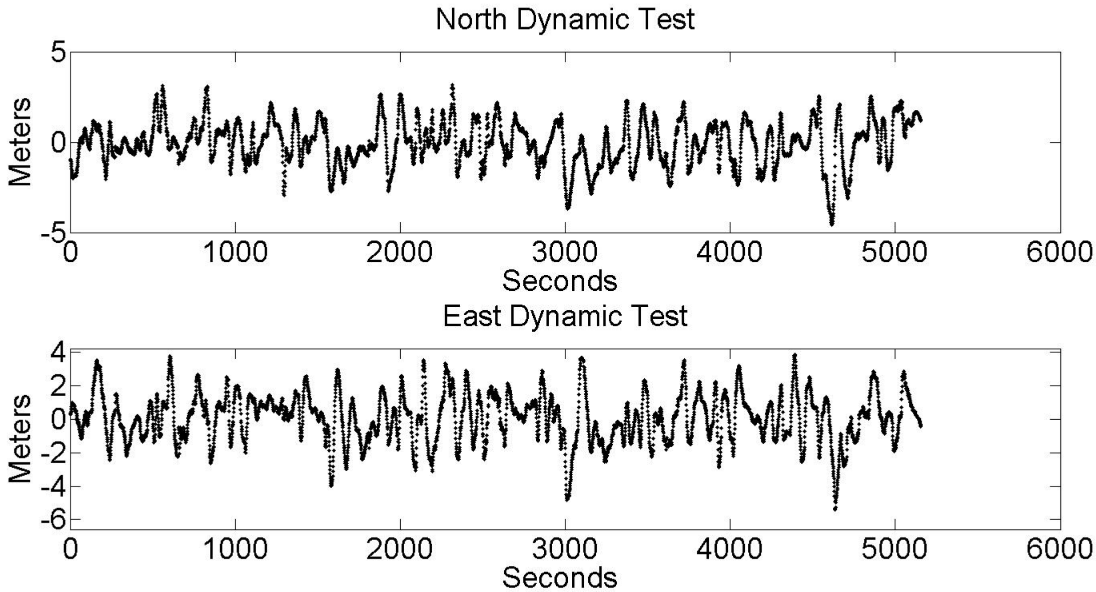

Figure 4.9: Dynamic Difference Between Live and Playback Position With GPSDO

Additionally, the PSD (Power Spectral Density) profile of the position solutions are different between live and playback data. As seen in Figure 4.10, the USRP has a smoothing affect to the error frequency. This smoothing is a result of the sampling process.

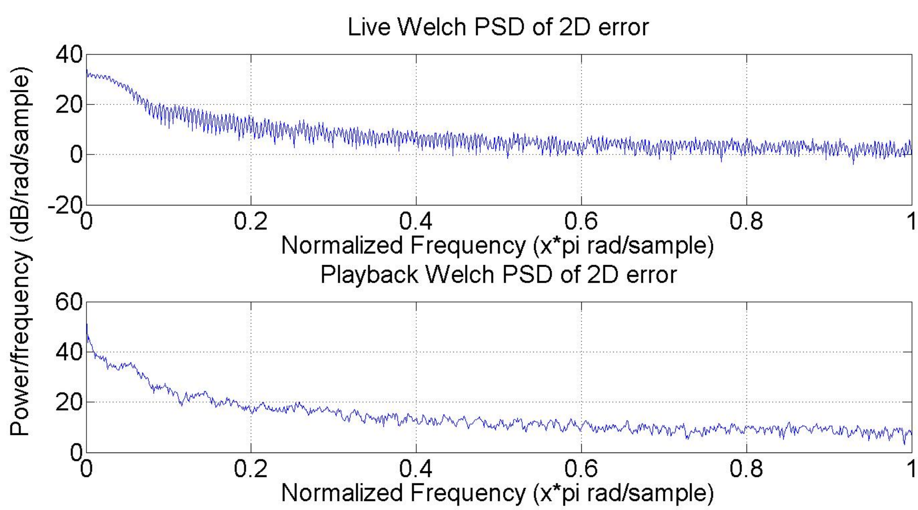

Figure 4.10: Dynamic Live vs Playback PSD of Position

In the figures below, the carrier to noise is provided for the dynamic data using the GPSDO. In this section an actual comparison between carrier to noise measurements taken with and without the GPSDO can be made. In Figure 4.6 the maximum carrier loss is around 5.5dB-Hz, while the measurements seen in Figure 4.12 has a max loss around 1.75dB-Hz. This comparison shows the magnitude of noise added to the GPS signal with and without the GPSDO.

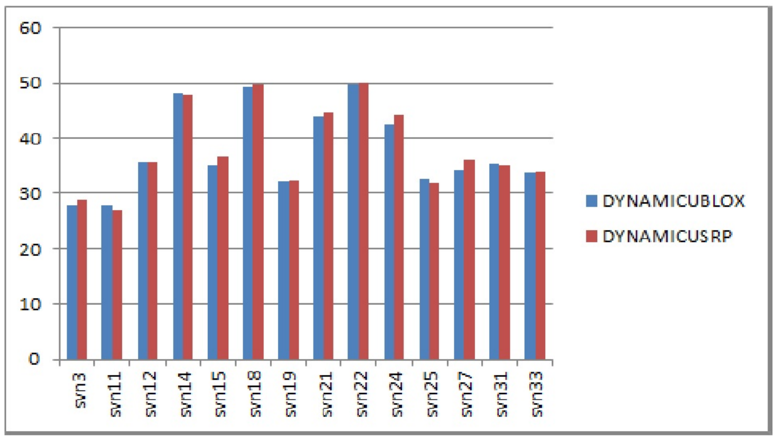

Figure 4.11: Dynamic Comparison of C/No with GPSDO

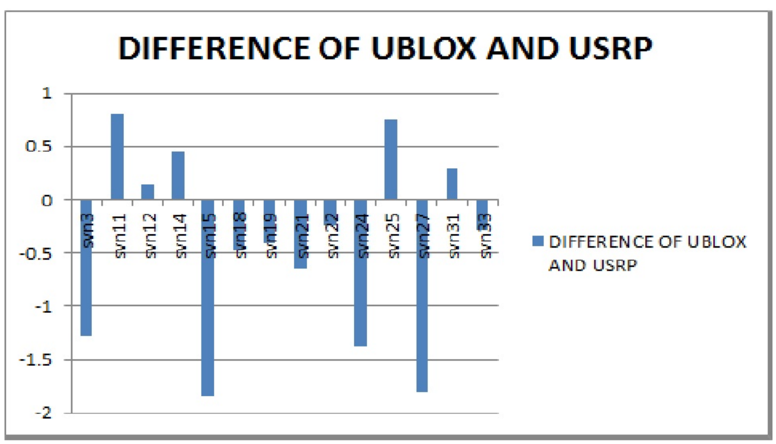

Figure 4.12: Dynamic Differenced of C/No with GPSDO

4.1.2.1 High Dynamic Testing

After observing how the dynamic runs differed from the static runs, the following question was proposed: How is dynamics correlated to error in Record and Playback created by the USRP? In this section, higher dynamic data will be compared to lower dynamics for any correlation between speed and accuracy of USRP.

High Dynamic Setup The high dynamic data set starts with one one minute of stationary data for a baseline. Then the vehicle drives along the path shown in Figure 4.13. This location is chosen because it is a nice controlled path that multiple tests can be conducted. This data is also calculated at 5 Hz because it is a much shorter data set.

Figure 4.13: High Dynamic Path

The data is taken in three different ways. First run was recorded at at 65 mph, this data was taken while driving 2-3 times around the track. The second test was recorded at 45 mph, which was also driven 2-3 times around the track. The final test was a high speed J turn to observe the sudden drift of the Ublox receiver.

High Dynamic Results The 2D plot of the path taken is shown in Figure 4.14. This shows the high dynamic path as well as, where the data was taken on the skid pad and demonstrates the controlled environment used for the J turn.

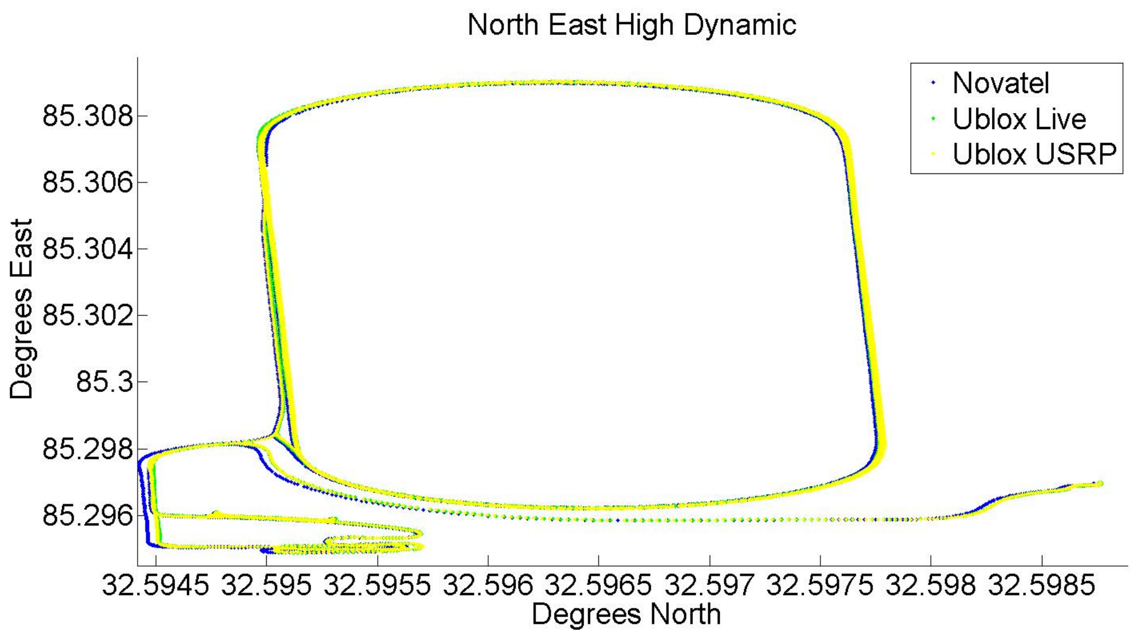

Figure 4.14: High Dynamic 2D Position with All 3

The data from the high dynamic tests will be split into statistical analysis for each of the three scenarios mentioned in setup. This will also only be done for the difference between record and playback. Figure 4.15 is the graphical representation of live and playback differenced. There are clear patterns derived from this specific data set and easily seen in the Figure 4.15. When running the statistics on the high dynamic data, the data was run individually by the three separate tests. As mentioned earlier the data set starts stationary and then goes to 65 mph for 430 seconds around the track. The vehicle then slows to 45 mph from second 431 to 900, and after getting in position multiple J turns were conducted between seconds 1140 till the end. Each part of the run can be seen here in Figure 4.15. These are separated in Figure 4.15 by dashed lines and tabulated in Table 4.5 in the statistics section below.

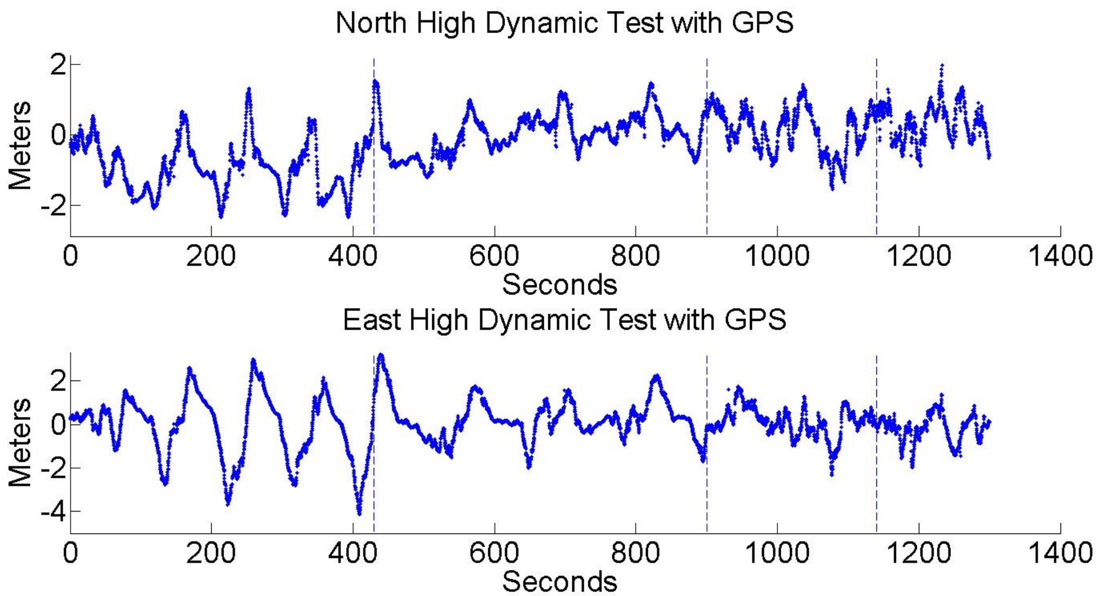

Figure 4.15: High Dynamic Ublox Live vs Ublox Playback

4.1.3 Statistics

The statistics in this section are gathered from dynamic data with the use of a GPSDO. Table 4.4 shows how the USRP performs with dynamic data. This can be compared to static data, and it is concluded that the USRP corrupts the dynamic data more than static. However this data does not quantify how effective the USRP is with all dynamic data.

When looking at the statistics for the data captured with the GPSDO, the data is split into two tables seen below. Table 4.3 shows the individual latitude and longitude errors. The data in 4.3 and 3.2 can be compared showing an error increase with dynamic data with the USRP. Table 4.4 shows the overall error for the 2D position solution.

Table 4.3: Latitude and Longitude GPS Statistics for Dynamic Data with GPSDO

Scenario	Mean Error (m)	Std Dev Error (m)	RMS Error (m)
Lat Ublox live	.93	1.39	1.67
Lat Ublox Playback	.98	2.22	2.42
Lat Ublox Live-Playback	-.05	-.82	-.75
Long Ublox live	.8	1.55	1.74
Long Ublox Playback	.69	2.45	2.55
Long Ublox Live-Playback	.1	-.91	-.81

Table 4.4: 2D GPS Statistics for Dynamic Data with GPSDO

Scenario	Mean Error (m)	Std Dev Error (m)	RMS Error (m)
2D Ublox live	2.02	1.32	2.41
2D Ublox Playback	2.97	1.86	3.52
2D Ublox Live-Playback	-.96	-.54	-1.1
2D Ublox Live-Playback Iterative	.99	.75	1.24

In Table 4.5 the statistics of the high dynamic data sets are separated out into their individual sections. This table shows how dynamics affect the USRP during record and playback. As can be seen from this table the USRP error is correlated to the speed of the vehicle. The data in the first two rows of Table 4.5 is fairly conclusive because it represents many types of data. However conclusive the data from the J turns is not because the short amount of data taken.

Table 4.5: High Dynamic Statistics

Scenario	Mean Error (m)	Std Dev Error (m)	RMS Error (m)
Data Run at 65 MPH	1.87	.74	2.01
Data Run at 45 MPH	.90	.66	1.12
J turns	2.01	1.12	.94

4.2 Dynamic Conclusions

The dynamic data started with data taken with the internal USRP clock. This data again confirmed the need for the GPSDO and shows how much of a change dynamic situations create for record and playback with the USRP. The GPSDO is then used to give a better USRP performance. This data is comparable to the static data taken with the GPSDO. The carrier to noise ratio is also compared with and without the GPSDO, showing significant noise is added to the signal due to the USRP clock. The RMS error increases by over 30% changing from static to dynamic data.

High dynamic data is taken to see if there is a correlation between speed and error from the USRP. From the high dynamic data, the faster the USRP moves when recording data the more noise specifically created by the USRP. This characteristic can be seen in Figure

4.15 and Table 4.5. Both show that there is a correlation, although the correlation is not quantified in this thesis.

Chapter 5

Analysis of USRP Record and Playback Using a Software Receiver

This chapter covers the general workings of a software receiver and how the GNSS-SDR receiver [9] is used to collect data. The error added by the USRP record and playback to the position using the GNSS-SDR software receiver is discussed. It will also cover many of the issues of using a software receiver, instead of a hardware receiver. Two software receivers were considered for this thesis, and the final decision of using the GNSS-SDR over the Akos receiver will be explained.

5.1 GPS Software Receiver Background

5.1.1 How receivers work in general

The software receiver takes a binary IF file, parses the data, and extracts the data bits from the IF data. To extract bits out of the IF file certain information must be known including: the sampling frequency, IF frequency, data type, etc. Once this and other information is known, the IF data is multiplied by the gold code for each satellite to acquire the signal. The bits are originally placed on the carrier by BPSK which phase modulates the carrier. This means if a data bit is transmitted the carrier phase is flipped. For instance, if the phase was 90 it would switch to -90 showing a bit transition. This method is used instead of frequency or amplitude modulation so that one frequency can carry all the satellites data. The entire 1023 bits of the gold code are placed in 1 ms of data, and one bit of the data message comes across about every 20 Ms. This is all done on the L1 carrier signal. To acquire a satellite, the signal needs to be multiplied by the gold code for each satellite and each chip; while the Doppler is simultaneously scanned for the best Doppler frequency. This is shown in Figure 5.1 where this "spike" denotes what Doppler and what bit of the gold code the signal is on.

Figure 5.1 is a graphical representation of acquisition. There are two methods of acquisition, series and parallel. This thesis shows the series method in Figure 5.1.

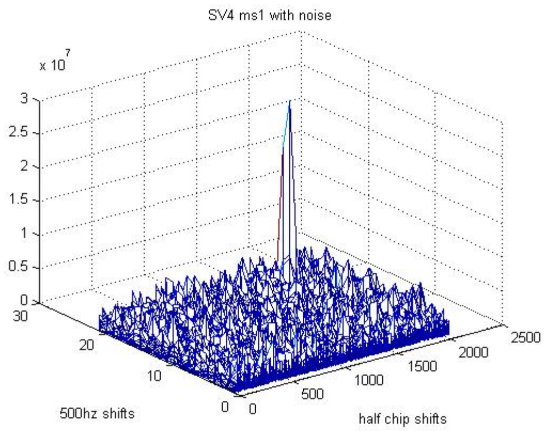

Figure 5.1: Series Acquisition

As can be seen in Figure 5.1 there is some noise around the spike. Depending on the location and signal strength, there may be enough noise to make the "spike" indistinguishable by the code. If the satellite is indistinguishable from the noise the satellite will not be acquired. If this is an issue due to RF noise or other external circumstances, the integration time can be increased to make the "spike" more prominent. This is done in Figure 5.2 using a 10ms integration period to show the difference.

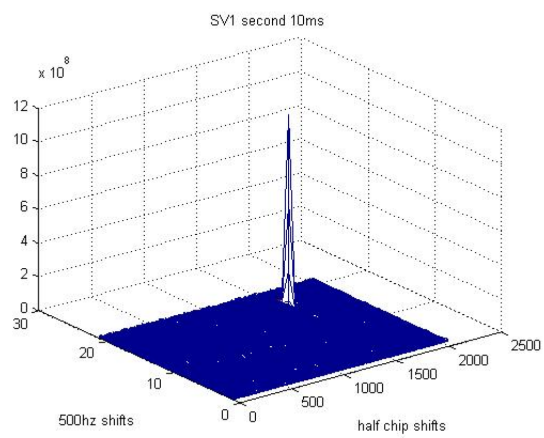

Figure 5.2: Series Acquisition 10Ms

Serial acquisition is a time consuming method of acquisition. A faster method is the parallel search method. Using a parallel method, the entire constellation can be acquired in about half the time that one satellite can be done in serial acquisition. The parallel method is however used by the GNSS-SDR for acquisition.

Once a satellite is acquired, the data bits can be extracted for information about the satellites. The message is transmitted at a much slower rate than the PRN code, so after the signal is acquired the preamble (start) navigation message is searched for, and each subframe starts with the string of bits called the preamble. Figure 5.3 from [2] is a representation of the 5 subframes for the GPS Navigation Data message. The first three subframes contain the ephemeris data and the last two contain the almanac. The almanac is transmitted in 24 separate frames in subframe 4 and 5. This takes approximately 12.5 minutes because of the amount of data received. It takes between 18 and 30 seconds to acquire a satellite, because it takes 6 seconds to receive each subframe. If the receiver does not start tracking the satellite at the start of the first subframe it will take the full 30 seconds. Each receiver can also lose signal, but store the individual subframes making tracking faster when the signal is reacquired. The only data required to start decoding satellite information comes in the ephemeris subframes. A complete GPS position can be calculated with ephemeris and pseudoranges of four satellites .

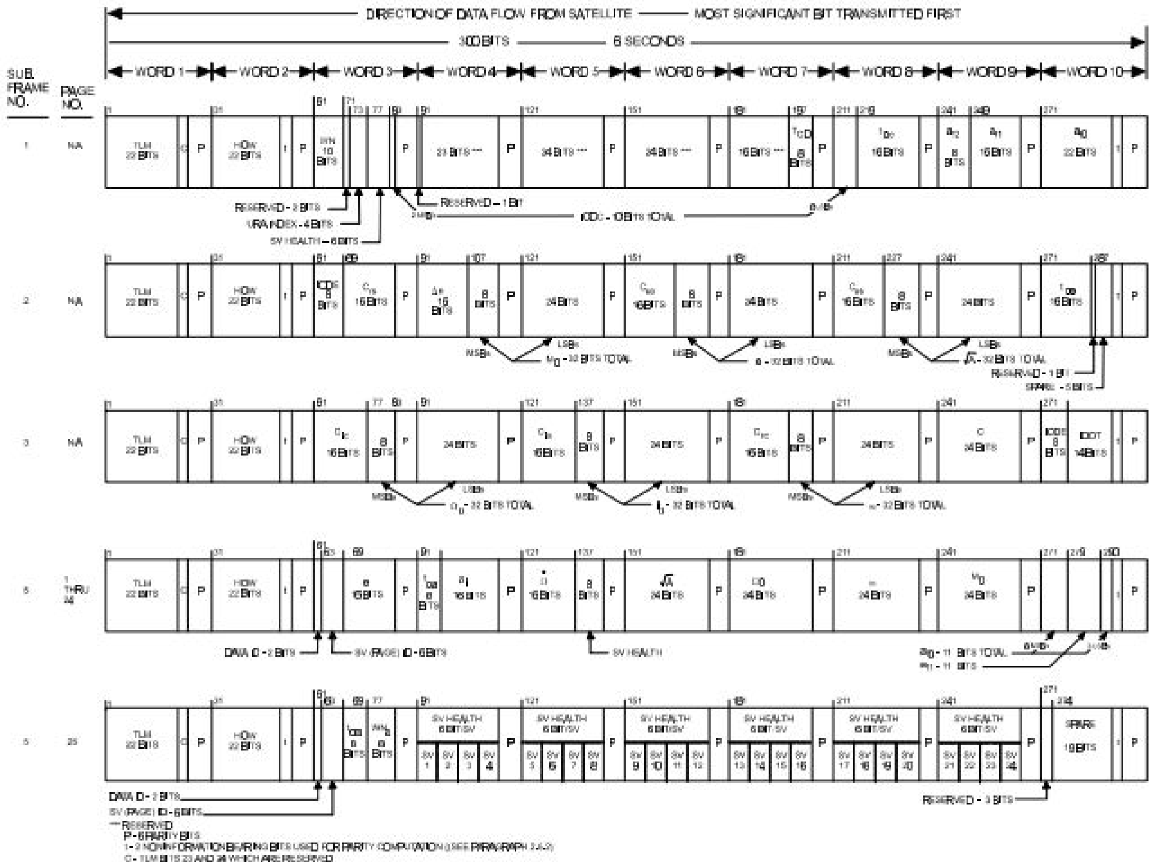

Figure 5.3: Sub Frames of GPS Ephemeris Message[2]

5.2 Software Receiver Selection

There were two software receivers considered for use in this thesis. The first one discussed, which is not used, is a receiver based off the software receiver in the book [3]. The Akos receiver code is written in Matlab with a large source of the code derived from code provided in the Akos book [3]. It is set up to take binary data in Matlab chip by chip to acquire and track GPS signal using a standard PLL loop. This receiver was modified to use the receiver to track satellites with USRP data. The modified version parses the code slightly different and can be tuned for better tracking. This receiver can acquire many satellites with high C/No measurements, but only 2 satellites were tracked with data used for this thesis. With the Akos receiver, it is simple to make changes at any point in the receiver.

The receiver chosen for the work in this thesis is the GNSS-SDR. The GNSS-SDR receiver is an open source receiver created to work with GNU Radio. It was not designed specifically for use with the USRP, but GNSS-SDR is used often with the USRP interface. With this receiver the writers of the code advise to make changes only to the configuration files. This does not give complete control over the receiver but is acceptable for this thesis. Because the code is written in C++ and designed to use GNU Radio manipulating the base code was not advised by the code writers. This receiver outputs positions, time, carrier to noise and more if requested.

GNSS-SDR is chosen to test the record vs playback abilities of the USRP for its interface simplicity. Though the Akos receiver is simpler to change, there were issues with parsing the data properly making it less desirable. The GNSS-SDR was made to work with the USRP and was therefore chosen.

5.3 Drawbacks

There are some drawbacks to using software receivers. Though the software receiver may have the capability to be tuned for specific scenarios quickly; to receive multiple data types major changes need to be made. While using the GNSS-SDR receiver, two different files are used. One is data captured as 2 bit binary and the other is 32 bit complex float solutions. Because the receiver is programmed for 32 bit complex float solutions the receiver could not use the 2 bit data. Another issue is the software receiver filter. A software filter does not run as fast as a hardware filter that is in most hardware receivers. Finally, one large issue with the software receiver is slight offsets in timing. This receiver can not use data captured with a GPSDO because of the increased clocking accuracy. GNSS-SDR was designed to work with GNU radio, but does not have a clocking type choice in the configuration file. This forced the data to be capture and used without the increased accuracy of the GPSDO.

5.4 Software Receiver Uses

This thesis focuses on the USRP's ability to record and playback GPS data. Even when dealing with the pseudoranges, the GPS signal was played back into the Ublox. In this section, the error from the recording process are isolated during the recording process, and eliminating the errors induced through the playback. The intention is to get position solutions from the IF data and compare those to the known position. The data recorded and shown in the results were recorded without a GPSDO and therefore can only be compared to data without the GPSDO. The position is compared to the truth position of the antenna on the roof of the Advanced Research Lab mentioned in Section 3.1.1.

5.5 Results From the Software Receivers

This data shows how the GNSS-SDR receiver deals with the error caused by the USRP. During testing many issues were discovered. While debugging these issues the inline amplifier was revisited. Figure 5.4 confirms the amplification does not need to be used by showing the magnitude of extra noise added by an inline amplifier in this test setup.

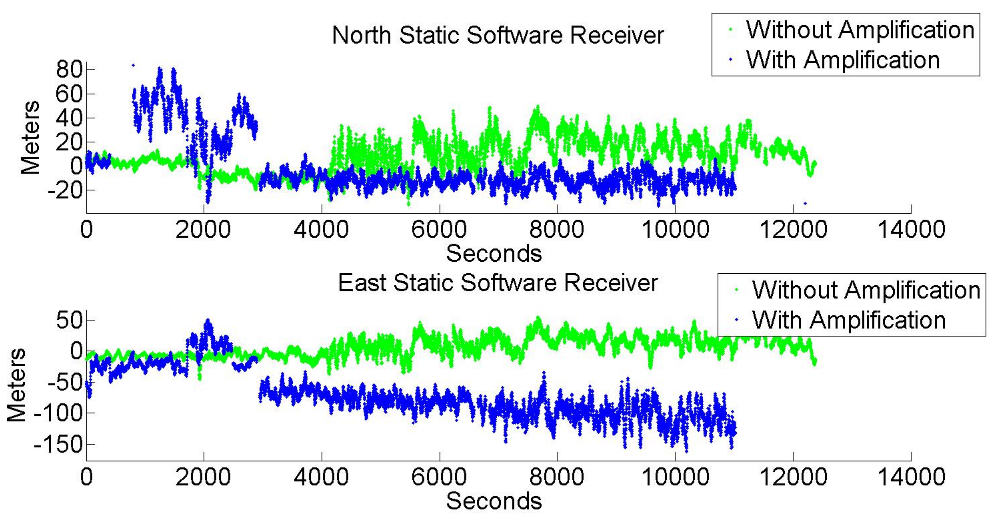

Figure 5.4: Live Software Receiver Data with and Without amplifier

The software receiver has multiple large spikes in position error without amplification. These spikes are short in duration and create havoc in the statistics. Because of this, there are three comparisons made here when looking at this data. These statistics are shown in Table 5.1, in which the static data without the GPSDO is compared to the software receiver statistics with position spikes and without position spikes. When removing these large position spikes from the data, as seen in Figure 5.5, the statistics are much more reasonable.

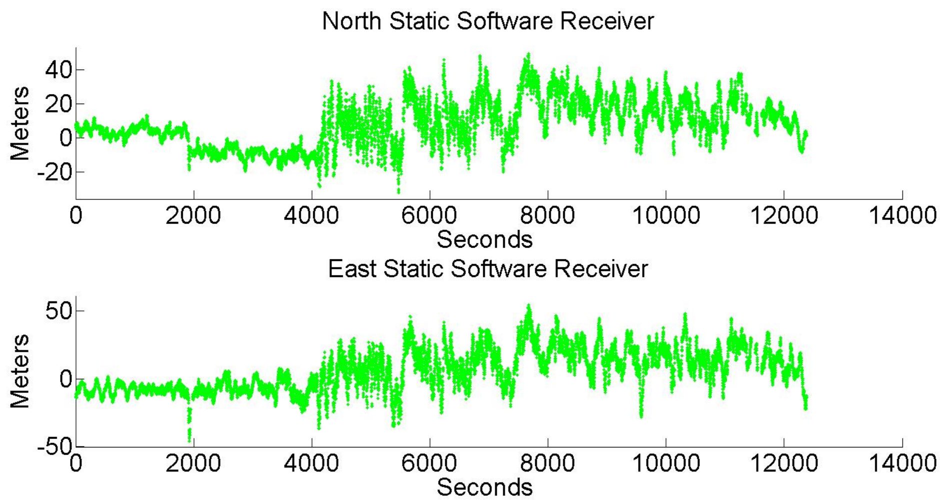

Figure 5.5: Live Software Receiver Data Without amplifier

Table 5.1 compares the software receiver appropriately with the static data taken without GPSDO. Each statistic is calculated from the position difference from truth. In the 2D Software Receiver Modulated row of Table 5.1, all position changes over 15 meters were discarded. The discarded data points numbered 186, which is approximately one percent of the data. The comparison between the modulated software receiver and the static playback from the USRP is valid because the low percentage of data discarded. Otherwise there would be no comparison between the record and playback and using a software receiver.

Table 5.1: Software Receiver vs. Static Data

Scenario	Mean Error (m)	Std Dev Error (m)	RMS Error (m)
2D Ublox USRP	17.91	16.87	24.60
2D Software Receiver	208.96	1754.51	3533.67
2D Software Receiver Modulated	18.98	12.49	22.72

5.6 Conclusions

The main goal of using the software receiver in this chapter is to isolate the significance of record in creation of position error with the USRP. The comparison made in this section did not use the GPSDO for reasons discussed earlier. One drawback of using the software receiver to compare to the Ublox is the change in error management. It is known that the Ublox manages the position error in a different way, but the software receiver gives a much more raw position measurement. Playback does affect the error, but the exact amount is not quantifiable for this study. As seen between the modulated software receiver and the static played back data, the standard deviation and RMS are both lower from the software receiver. Because the software receiver statistics (excluding the statistically void points) is slightly better than the data from the Ublox, and the repeatability tests shows that not much error is added in playback. It is concluded that the error increase much more during record than playback.

Chapter 6

Conclusions and Future Work

6.1 Observations and Conclusions

6.1.1 Limitations of USRP Evaluation

Limitations and shortcomings of the software and hardware are discussed in this section. This section provides important segway into further work as a way to save time and improve results. Some mistakes made during testing are discussed, while others limitations with the USRP itself are discussed.

While gathering pseudorange data, there were multiple limitations. The first issue was the software used for taking the data. The software Go-GPS requires Matlab and a constant internet connection to work. Some errors occurred when compiling the data at the end which was found late in post processing. When looking at these lower level measurements, certain data points were dropped from individual satellites at different points. Some were not seen in the live data and others in the playback. This could not be explained from the research done in this thesis.

With the dynamic testing, the first part of "normal" dynamic data was taken around a standard street. The speed ranged from 25-55 mph but all of it was smooth driving with gradual acceleration. The main signal errors were caused by degraded internet connectivity which created spikes in the RTK position. There was a lot of drift from the high dynamic data collected at the track. Both clock drift and position drift were observed. The only problem with the CSAC data set, was the large amount of movement seen at the beginning of the data set. This seems to be due to the second data set being recorded from a cold start of the receiver. During all the tests with the Ublox, the starting method was taken into account for post process reasons. It was noted if the receiver started from a cold start, warm start, or hot start.

Because the software receiver is designed to work with a TCXO, it did not get a position solution when using the GPSDO. Because of this, the data was recorded without the aid of the GPSDO for timing. During the software receiver testing, a test is derived to see the effects of recording and playing back with different clock disciplines. When conducting this test, if the clock was not the same during record and playback there would be no acquisition of GPS signals.

6.1.2 Conclusions

The initial static result that compares the GPSDO and NON-GPSDO results shows the need for accurate timing. Section 3.1.3 also shows the validity of record and playback for static data when using more accurate timing. In Section 3.2 the CSAC was tested to see if an even more accurate clock would give a more accurate position solution. The CSAC does improve the position solution with a RMS error approximately 50 percent better than data with a GPSDO. Because of this increase, it is concluded that the more accurate the clock the better the record and playback results.

When testing for the validity of playing one data set back multiple times, the change in position error is quite small. This validates the playback ability of the USRP and the consistency of results. From the repeatability testing the results show errors between test are approximately 1% of the overall error created by the USRP. In addition to playing the signal back multiple times to one receiver, an attempt is made to play same data to different receivers. Each receiver reacts to the error created by the USRP in a similar way. Because the statistics look proportionally correct the data recorded by the USRP can be tested across receiver platforms.

The conclusions that were drawn form the result of the pseudorange testing were interesting. The first noticeable result was the difference in availability of pseudoranges between record and playback. The pseudorange measurements were not always captured at the same time; some times there were measurements captured in the live data only and other times the measurements were captured in the playback data only. This small piece of evidence shows the amount of signal that is changed by recording and playing back the IF. The lack of pseudoranges can be caused by any number of the following: dropped bit while recording to the hard drive, offset of the sample rate, spike in the noise and loss of signal, and degradation through the USRP at certain times. These can be examined in the future in more detail. Also during the pseudorange test a large change in doppler was seen. When looking at the data it seems to mimic of an over damped system moving to steady state. This can account for some of the issues when recording and playing back when an initial offset is seen. Though the changes are large in the beginning for longer data sets the USRP works adequately and gives accurate position data.

The dynamic data shows a weakness of the USRP, the error increases significantly when used in a dynamic situation. The USRP can be used for dynamic situations but it is not as accurate as static scenarios. The higher the dynamics, the larger the position error created by the USRP. This can be seen graphically in Figure 4.15, which shows the higher speed causing more error between the live and played back data. Because of this, it is suggested that the USRP is used more for static and low velocity testing.

Finally, from the software receiver testing, it is concluded that both record and playback add error to the position. The error from the clock is compounded in record and then playback. It was determined that recording adds much more error than playback. Also it was discovered during this test that the same clock has to be used for record and playback or there will be no position solution.

6.2 Future Work

6.2.1 Measuring Difference Between Clocks

This thesis discovered the importance of timing for the USRP. Some effects of the clocks were explored, but more correlation may be found with different ways to collect data. Many of the sources used for this thesis explored some clock drift over time, but they have not been correlated to accuracy of GPS record and playback position. The error created by the USRP clock needs to be correlated to position accuracy.

6.2.2 From IF to Pseudorange

In Section 3.4, conclusions are drawn about the error on the pseudoranges. The noise creating the error is not introduced at the pseudorange level. Because of this, the error needs to be traced back further to the source of the error at the IF level. A possible way to do this could start by recording IF multiple ways and looking at the changes in error between them. To do this a software receiver can be developed to see the errors from multiple IF recorders.

6.2.3 GPS Simulator

To more completely characterize the error on the USRP during record and playback of GPS data, a simulator can be used. The simulator can output an RF signal that does not have any errors on it. This can be used to see what errors the USRP adds by itself. The simulator can also add specific types of errors, this method can pinpoint types of errors that the USRP enhances. Using a simulator to pinpoint specific error modes will allow for better use of the USRP in the future.

6.2.4 Mitigating Error

If the error created by the USRP can be predicted by an equation, the error can be predicted and controlled in certain scenarios. With a completed model of the error created by the USRP record an playback can be used to test specific qualities of GPS receivers. Errors can be added and subtracted to simulate different error.

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