ABSTRACT

A USRP-BASED FLEXIBLE GNSS SIGNAL RECORDING AND PLAYBACK SYSTEM: PERFORMANCE EVALUATION AND STUDY

by Ruihui Di

Global Navigation Satellite Systems (GNSS) signals are often subjected to both manmade and natural interferences such as RF jamming, ionosphere scintillation, multipath, and signal anomaly. In order to achieve desired navigation application performances, advanced receiver processing or multi-sensor integration algorithms must be developed to mitigate these interferences. A flexible multi-frequency multi-constellation GNSS signal generator is an important enabler of robust GNSS receiver research and development. There is a growing number of companies that offer high end GNSS signal simulators or generators. These high end signal simulators or generators, however, are expensive and can be cumbersome. This thesis presents a reconfigurable wideband multi-frequency multi-constellation GNSS signal recording and playback system based on the Universal Software Radio Peripheral (USRP) N210 model. The USRP-N210 based recording and playback system is low cost, portable, and can be reconfigured to record and transmit the entire family of GNSS signals when paired with appropriate RFX daughter boards and controlled by an external low phase noise oscillator. The source of the signal can be pre-recorded digital samples obtained from other RF front ends or arbitrary waveform samples generated using MATLAB programs. An adjustable low noise signal amplifier mounted between the USRP-N210 output and the transmitting antenna was used to control the transmitted power of the signal. A spectrum analyzer was used to monitor the transmitted signal. The GPS L1, L2, L5, and GLONASS L1 and L2 signals were recorded and re-transmitted using the multi-GNSS signal recording and playback system. The receiver output and the transmitted signal are processed by both a NovAtel OEM receiver and software receivers and the results are compared with the original signal parameters to demonstrate the accuracy of the playback system.
A USRP-BASED FLEXIBLE GNSS SIGNAL RECORDING AND PLAYBACK SYSTEM:
PERFORMANCE EVALUATION AND STUDY

A Thesis

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Faculty of Miami University
in partial fulfillment of
the requirements for the degree of
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Department of Electrical and Computer Engineering

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### Acronyms

<table>
<thead>
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<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC</td>
<td>Analog-to-Digital Converter</td>
</tr>
<tr>
<td>API</td>
<td>Application Programming Interface</td>
</tr>
<tr>
<td>BOC</td>
<td>Binary Offset Carrier</td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary Phase Shift Keying</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
</tr>
<tr>
<td>CL</td>
<td>Civilian Long length code</td>
</tr>
<tr>
<td>CM</td>
<td>Civilian Moderate length code</td>
</tr>
<tr>
<td>Beidou</td>
<td>A Chinese Satellite Navigation System</td>
</tr>
<tr>
<td>C/N₀</td>
<td>Carrier to Noise Ratio</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital-to-Analog Converter</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DLL</td>
<td>Delay-Locked Loop</td>
</tr>
<tr>
<td>FLL</td>
<td>Frequency-Locked Loop</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field-Programmable Gate Array</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>FEC</td>
<td>Forward Error Correction</td>
</tr>
<tr>
<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>GLONASS</td>
<td>Global Navigation Satellite Systems</td>
</tr>
<tr>
<td>GALILEO</td>
<td>A global navigation satellite system currently being built by the European Union (EU) and European Space Agency (ESA)</td>
</tr>
<tr>
<td>GEO</td>
<td>Geographic Coordinate System</td>
</tr>
<tr>
<td>ICD</td>
<td>Interface Control Document</td>
</tr>
<tr>
<td>MATLAB</td>
<td>Matrix Laboratory</td>
</tr>
<tr>
<td>NCO</td>
<td>Numerically Controlled Oscillator</td>
</tr>
<tr>
<td>NRZ</td>
<td>Non-Return to Zero</td>
</tr>
<tr>
<td>NH</td>
<td>Neuman-Hofman</td>
</tr>
<tr>
<td>NH¹⁰</td>
<td>10 bits Neuman-Hofman Code</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>NH20</td>
<td>20 bits Neuman-Hofman Code</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
<tr>
<td>OCXO</td>
<td>Oven-Controlled Crystal Oscillators</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase-Locked Loop</td>
</tr>
<tr>
<td>PRN</td>
<td>Pseudo-Random-Noise</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>SV</td>
<td>Space Vehicles</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>TCXO</td>
<td>Temperature Compensated Crystal Oscillator</td>
</tr>
<tr>
<td>TRIGR</td>
<td>Transform-domain Instrumentation GPS Receiver</td>
</tr>
<tr>
<td>USRP</td>
<td>Universal Software Radio Peripheral</td>
</tr>
<tr>
<td>UHD</td>
<td>USRP Hardware Driver software</td>
</tr>
<tr>
<td>UTM</td>
<td>Universal Transverse Mercator Coordinate System</td>
</tr>
</tbody>
</table>
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Chapter 1

Introduction

1.1 Problem Statement and Objectives

The widespread application and utility of the Global Positioning System (GPS) has led to a new era of growth in satellite-based navigation technologies. Four Global Navigation Satellite Systems (GNSS) now coexist in the world: the US’s GPS, Russia’s GLONASS, China’s Beidou, and Europe’s Galileo. GNSS and applications, however, face many challenges. GNSS signals are commonly subjected to both manmade and natural interferences such as RF jamming, ionosphere scintillations, multipath, and signal anomaly. In order to achieve the desired navigation application performance, advanced receiver processing or multi-sensor integration algorithms must be developed to mitigate these interferences. A flexible GNSS signal generator is an important enabler of robust GNSS receiver research and development.

There are a growing number of companies that offer high-end GNSS signal simulators or generators, such as SPIRENT, Agilent, Frontline, etc. One problem of these high end signal simulators or generators is their high costs. Additionally, these instruments can be cumbersome in size. For example, the Genos GNSS Satellite Simulator and the Spirent GSS6300 GNSS Signal Generator are two commonly used GNSS signal generators. The weight for the above two generators is 15kg in weight [1] and 6.5kg [2] respectively. For this reason, we developed a low cost, portable, and flexible GNSS signal and interference signal generator and playback system based on a general purpose software radio front end, the Universal Serial Radio Peripheral (USRP) family of devices. Compared with the commercial GNSS signal generator, the USRP based signal generator is just 1.2kg in weight [3].

Currently, there are many Universities and industry units in the world use USRP series products as the tool to complete their researches. For instance, the USRP was once used as an underwater acoustic modem by Northeastern University, Boston, MA, and the work is the first time that the USRP/GNU Radio is applied to an UWA channel and represents an exciting branch into a field that has a need for cost-effective and configurable modems [4]. Additionally, the
USRP has already been used for digital wireless communication research by the University of Texas at Austin, Austin, TX, USA. The physical layer exploitation wireless networking and communications were carried out by the group department of Electrical and Computer Engineering at this university [5]. Moreover, the researchers, Alison Brown, Reece Tredway, and Robert Taylor who come from NAVSYS Corporation once used the USRP for GPS signal simulation development. The application of USRP has already been extended to many fields.

The objective of this thesis is to develop a USRP-based platform that can record and playback multi-GNSS system signals, such as GPS, GLONASS, GALILEO and BEIDOU, etc. The performance comparison will be evaluated through GPS L1, L2C, L5, and GLONASS L1 and L2 signals in this thesis.

1.2 Hardware and Software Environment

The USRP product family includes a variety of models that use a similar architecture [6]. A motherboard contains the following subsystems: FPGA, DACs, ADCs, clock generation and synchronization, host processor interface, and power regulation. These are the basic components that are required for baseband processing of signals. A modular front-end, called a daughterboard, is used for analog operations such as up/down-conversion, filtering, and other signal conditioning. This modularity permits the USRP to serve applications that operate between DC and 6 GHz. A USRP-N210 mother board paired with appropriate RFX daughter boards can generate all GNSS signals controlled by a personal computer. The source of the signal can be pre-recorded digital samples obtained from specific RF front end or arbitrary samples generated using MATLAB programs. An adjustable low noise signal amplifier mounted between the USRP-N210 output and the transmitting antenna was used to control the transmitted power of the signal. A spectrum analyzer can be used to monitor the transmitted signal. Fig.1.1 shows the conceptual diagram of USRP-N210 based GNSS signal recording and playback system.
The USRP product line includes several generations of boards: the original USRP, USRP E100, USRP2, and USRP-N210. Some key components differences among the USRP-N210, USRP2 and USRP are listed in Table 1.1. The latest product, USRP-N210, clearly offers the most among them with higher speed, better performance, and increased flexibility [7]. So, in designing our GNSS recording and playback system, we chose the USRP-N210 mother board. UHD which is the official hardware driver for USRP-N210 is installed on the Ubuntu 11.04 Linux operating system to control the recording and playback system operation.

Table 1.2 shows the daughter boards and its corresponding available frequency and functions. In this thesis, the RFX1800 and RFX1200 were mainly used to recording and playback the simulated and real GNSS signals.
### Table 1.1 Key Components Differences among USRP-N210, USRP2 and USRP [7]

<table>
<thead>
<tr>
<th>Components</th>
<th>USRP-N210</th>
<th>USRP2</th>
<th>USRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Range</td>
<td>0~5.9GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FPGA</td>
<td>Xilinx Spartan 3A</td>
<td>Xilinx Spartan 3-2000</td>
<td>Altera Cyclone</td>
</tr>
<tr>
<td>DACs</td>
<td>Two 400MS/s 16-bit</td>
<td>4 128MS/s 14-bit</td>
<td></td>
</tr>
<tr>
<td>ADCs</td>
<td>Two 100MS/s 14-bit</td>
<td>4 64MS/s 12-bit</td>
<td></td>
</tr>
<tr>
<td>Sampling Freq.</td>
<td>50MHz</td>
<td>16MHz</td>
<td></td>
</tr>
<tr>
<td>PC Connect.</td>
<td>Gigabit Ethernet</td>
<td>USB 2.0</td>
<td></td>
</tr>
</tbody>
</table>

### Table 1.2 USRP Series Daughter Boards [8]

<table>
<thead>
<tr>
<th>Name</th>
<th>Available Freq.</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>BasicRX</td>
<td>1-250 MHz</td>
<td>Receiver</td>
</tr>
<tr>
<td>BasicTX</td>
<td>1-250 MHz</td>
<td>transmitter</td>
</tr>
<tr>
<td>LFRX</td>
<td>DC-30 MHz</td>
<td>Receiver</td>
</tr>
<tr>
<td>LFTX</td>
<td>DC-30 MHz</td>
<td>transmitter</td>
</tr>
<tr>
<td>TVRX2</td>
<td>50-860 MHz</td>
<td>receiver</td>
</tr>
<tr>
<td>DBSRX2</td>
<td>800MHz-2350 MHz</td>
<td>receiver</td>
</tr>
<tr>
<td>WBX</td>
<td>50 MHz to 2.2 GHz</td>
<td>Transceiver</td>
</tr>
<tr>
<td>SBX</td>
<td>400 MHz to 4.4 GHz</td>
<td>Transceiver</td>
</tr>
<tr>
<td>RFX900</td>
<td>750MHz-1050 MHz</td>
<td>Transceiver</td>
</tr>
<tr>
<td>RFX1200</td>
<td>1150MHz-1450 MHz</td>
<td>Transceiver</td>
</tr>
<tr>
<td>RFX1800</td>
<td>1500MHz-2100 MHz</td>
<td>Transceiver</td>
</tr>
<tr>
<td>RFX2400</td>
<td>2300MHz-2900 MHz</td>
<td>Transceiver</td>
</tr>
<tr>
<td>XCVR2450</td>
<td>2.4-2.5 GHz &amp; 4.9-5.9 GHz</td>
<td>Transceiver</td>
</tr>
</tbody>
</table>
Figure 1.2 shows the block diagram of USRP-N210 digital signal processing hardware and software environment. Figure 1.3 is the corresponding snapshot of the real data collection and playback system in the Software Receiver Lab at Miami University. The real RF GNSS signal first impinges on the NovAtel GPS-703-GGG antenna, which is an active antenna. The antenna is connected with a 4-way splitter followed by a TRIGR front end [9], a NovAtel OEM4 dual frequency hardware receiver, and a USRP-N210 front end. One important use of NovAtel OEM4 dual frequency hardware receiver is that it can provide 5 DC volts power supply to power up the NovAtel GPS-703-GGG antenna via the DC port in the 4-way splitter. The TRIGR front end is an instrumentation quality RF front end built at the Ohio University Avionics Engineering Center [9]. It provides simultaneous access to four channels (two GPS L1s, one L2 and one L5). The TRIGR front end works at a fixed sampling frequency of 56.32MHz and IF frequency at 13.68MHz with configurable bit resolution at 2, 4, 8, and 16. The sampling frequency of USRP-N210 can be set manually. We set the frequencies at 5MHz or 8MHz for GPS L1 and L2C and 20MHz for GPS L5 and GLONASS L1&L2 signals.
1.3 Signal Processing on USRP-N210 Board

The basic designing philosophy of USRP is that all waveforms processing operation will be completed on the host CPU, such as modulation and demodulation. All other operations, such as digital down conversion, sampling and interpolation and other high-speed general-purpose operation will be completed on the FPGA board. Fig.1.4 is the block schematic diagram of digital signal processing on USRP-N210 FPGA board. For signal recording purposes (Fig.1.4 (a)), the RF signal received by the antenna will first undergo a low IF-based pre-processing unit which combines the traditional super-heterodyne and analog complex down-conversion technology as shown in Fig.1.5 [10].

After pre-processing, the analog data will pass through the ADC units where the signal will be sampled with the sampling rate $fs$. The digital signal down-conversion process will be completed in the FPGA (shown inside the red dashed line area). When the bandwidth decimation factor is $N$, the sample rate of the output digital signal after passing through the decimating low pass filter is $fs/N$. The decimated digital signal which is consisted of I and Q with 16 bit resolution will be transferred to the host PC via the Gigabit Ethernet interface. When the USRP-N210 used in transmitting mode (Fig.1.4(b)), the implementation is a fully reversed process.

Paired with specific daughter boards, the USRP-N210 is capable of processing signals from DC to 5.9GHz. Table1.2 lists the current available daughter boards that can be used for radio
frequency signal processing. The RFX1800 (1500 MHz-2100 MHz) covers GPS and GLONASS L1 band, while RFX1200 (1150 MHz -1450 MHz) covers the GPS L2 and L5 and GLONASS L2 band. In our project, we select both RFX1800 and RFX1200 daughter boards to receive and transmit the GPS and GLONASS signals.

Fig.1.4. Block Schematic Diagram of Digital Signal Processing on FPGA Board, (a) for GNSS signal recording, (b) for signal transmitting

Fig.1.5. Signal Down-conversion Architecture (from Ref. [10])

1.4 Thesis Organization

The remaining thesis is organized in the following manner. In Chapter 2, the configuration for Multi-GNSS signal recording and playback system is introduced. Chapter 3 describes real and simulated GNSS signal processing via USRP-N210Chapter 4 addresses the issue of
overflowing and underflowing encountered in using the USRP-N210 as signal recording and playback system. The conclusion and future work are summarized in Chapter 5.
Chapter 2
Multi-GNSS Signal Recording and Playback System Configuration

This chapter presents the multi-GNSS signal recording and playback system configuration established in software receiver Lab at Miami University. The software receiver tracking processing loop is also introduced in this chapter.

2.1 GNSS Signal Recording System Setup

Fig. 2.1 shows the data receiving instrument configuration which was set up in the Software Receiver Lab at Miami University. The real RF GNSS signal first impinged on the NovAtel GPS-703-GGG antenna, which is an active antenna. The antenna is connected with a 4-way splitter followed by a NovAtel OEM4 dual frequency hardware receiver, and three USRP-N210 front ends. Both Fig. 2.2 and Fig. 2.3 show the snapshot of the laboratory setup. One important use of NovAtel OEM4 dual frequency hardware receiver is that it can provide 5 DC volts power supply to power up the NovAtel GPS-703-GGG antenna via the DC port in the 4-way splitter. The TRIGR front end, as is shown in Fig. 2.1, used here to provide the external OCXO clock to synchronize the three USRP-N210 front ends. The USRP-N210 based recording systems generates near-zero IF frequencies. The sampling frequency of USRP-N210 can be set manually.

Fig. 2.1. Block Diagram of Real GNSS Data Collection System at Miami University
Fig. 2.2. Snapshot of the Real Data Collection System

Fig. 2.3. Snapshot of the Real Data Collection System with Spectrum Analyzer (Left) and Clock Splitter (right)
2.2 GNSS Signal Playback System Setup

When using the USRP as a playback system, the source data can be simulated data or real GNSS signal data. Real baseband GNSS signal data can be collected using a specific RF front end. Fig.2.4 shows the block schematic diagram of playback system with two USRP-N210s. Fig.2.5 shows the snapshot of real data recording and playback system with the TRIGR instrument, a Septentrio PolaRxS receiver, two daughter boards, and a reference clock splitter.

![Block Schematic Diagram of Playback System with two USRP-N210s.](image)

In Fig.2.4, PC1 and PC2 control the two USRP-N210s respectively. One is acted as the data transmitting controller, and the other one as the data recording controller. The two USRP-N210s were synchronized by the same external clock in TRIGR front end described above. Since the two USRP-N210s can output DC voltage, the DC block units after the output and before the
input of the USRP-N210 are needed to protect the units. Between the two DC blocks, we used an adjustable attenuator and a 1 meter cable line to connect the two USRP-N210s to ensure sufficient attenuation of the playback system. The data recorded via USRP-N210 will be processed by software receiver.

Fig 2.5. Snapshot of the Real Data Recording and Playback System with TRIGR Instrument (Upper Left), Septentrio PolaRxS (Bottom Left), Two Daughter Boards for Playback Purpose (Upper Right) and Reference Clock Splitter (Bottom Right)

2.3 GNSS Software Receiver Processing

We evaluate the performance of the USRP-N210 playback system based on GNSS signal observables, such as the carrier-to-noise ratio \((C/N_0)\) and carrier phase noise \([11]\). Carrier phase and code phase delay errors are also important measure of the playback system. These quantities were not evaluated in this project because the specific goal of the playback systems in this project is to study ionosphere scintillations. The absolute measure of code phase and carrier phase is not critical for this particular application. In future work, we suggest that the code phase and carrier phase errors should be evaluated. GPS L1, L2CM, L5I, and GLONASS L1 and L2
signals were acquired, tracked, and analyzed in this project. Acquisition of GPS signals is initiated with a FFT-based two dimensional search of the L1 signal CA code phase and carrier Doppler frequencies [12].

The software receiver tracking loops consist of a carrier lock loop that tracks the carrier frequency and phase and a code delay lock loop (DLL) that tracks the PRN code phase [12, 14]. Signal tracking loop is usually initiated by acquisition that designed in software or hardware receivers. The incoming signal will first be mixed with two locally generated orthogonal sinusoids. The mixing results are then integrated and sent to the discriminator. The output of the discriminator is filtered and used as the input of the NCO to update the local carrier center frequency [11, 13]. An Early-Prompt-Late DLL with a half chip correlator spacing is used in the software receiver for the code tracking. The pre-integration time and equivalent noise bandwidth were used as the primary parameters for the tracking loop to adjust its tracking performances. The changes of baseband signal parameters, such as code phase transition, carrier phase changes, will be tracked and recovered from the measurements.

### 2.3.1 Carrier Tracking

The output estimations of carrier signal parameters from carrier tracking loops are carrier frequency, carrier phase, and carrier amplitude. The overview of conventional phase lock loop (PLL) is shown by Fig.2.6. A conventional GPS signal tracking algorithm, as shown in Fig.2.7, is used to generate the signal observables for performance evaluations. The input signal is correlated with a locally generated sine and cosine reference signal to produce the accumulated Integrate and Dump (I&D) outputs, which we called as the in-phase and quadrature phase measurements. The accumulated I and Q measurements will be used by a Costas PLL discriminator defined by Eq.2.1 to produce carrier phase estimation. The discriminator outputs will then be filtered and the filtered results are used to generate the carrier reference signal for further signal processing.

\[
\hat{\phi} = \text{atan}(\frac{Q}{I})
\]  

(2.1)
2.3.2 Tracking Loop Filter Design

The order and bandwidth are two key parameters in designing a conventional PLL tracking loop. Generally, the order of the loop filter is chosen based on signal’s dynamics. When the
signal is in high dynamics, a higher order loop filter is better when implemented to accommodate platform acceleration. The bandwidth of the loop filter can be defined as:

\[ B_n = \frac{1}{|H(0)|^2} \int_0^\infty |H(2j\pi f)|^2 df \]  \hspace{1cm} (2.2)

Where \( H(2j\pi f) \) is the transfer function of the PLL tracking loop. We can choose a third order loop filter to accommodate the high signal dynamics, and it will ensure that the system is stable if the loop filter bandwidth \( B_n \) is smaller than 18Hz [14]. When implementing a tracking filter loop, we can reference the existing analog filter design. Fig.2.8 shows a continuous time s-domain block diagram of a 3rd order loop filter [14].

![Block diagram of a 3rd order loop filter](image)

The input of the loop filter is carrier phase error which was generated by the phase discriminator. In Fig.2.8, the 1/S block represents an integrator in the analog domain, and the parameter \( \omega \) represents the loop filter’s natural frequency which is related to the loop bandwidth \( B_n \) by Eq.(2.3). The other parameters in the loop filter in Fig.2.8 can be typically selected as Eq.(2.4) and Eq.(2.5) [14]:

\[ B_n = 0.7845 \omega \] \hspace{1cm} (2.3)

\[ a_3 = 1.1 \] \hspace{1cm} (2.4)

\[ b_3 = 2.4 \] \hspace{1cm} (2.5)

There are several methods that can be used to convert the integration operation shown in Fig.2.8 from analogous to the digital domain, such as impulse invariance method, bilinear transformation etc. The block diagram of a bilinear transformation is shown by Fig.2.9. The
bilinear transformation equation is shown by Eq.2.6. A digital implementation of the loop filter can be realized by replacing all $S$ terms with $\frac{2Z-1}{TZ+1}$.

$$H_d(Z) = H_a(S)\bigg|_{S=\frac{2Z-1}{TZ+1}} = H_a\left(\frac{2}{T}\cdot\frac{Z-1}{Z+1}\right)$$

(2.6)

Fig.2.9 Block Diagram of a Bilinear Transformation
Chapter 3

Real and Simulated GNSS Signal Processing

There are six sections in this chapter. The first section introduces both GPS and GLONASS signal generation. The second and third sections evaluate the performance of simulated GNSS and real GNSS playback signals respectively. The reference clock effect is discussed in the fourth section. The tracking performance comparison is presented in section five. The last section compares positioning result accuracy between the original recorded signal and the playback signal.

3.1 GNSS Simulated Signal Generation

3.1.1. GPS Signal Generation

The polynomials and signal structures to generate GPS L1, L2C are completely described in GPS Interface Control Document (ICD-GPS-200C). The description of the new GPS L5 signal is also available in IS-GPS-705. The GPS signal modulation format at L1 and L2C are shown by Fig.3.1 and Fig.3.2 respectively.

![Fig.3.1 GPS Signal Modulation Format at L1](image_url)
The general expression for L1 and L2 signal are given by:

\[
 s_{L1}^{(k)}(t) = \sqrt{2P_c} \cdot C^{(k)}(t) \cdot D^{(k)}(t) \cdot \cos(2\pi f_{L1}t + \theta_{L1}) + \sqrt{2P_1} \cdot P^{(k)}(t) \cdot D^{(k)}(t) \cdot \sin(2\pi f_{L1}t + \theta_{L1})
\]  

(3.1)

\[
 s_{L2}^{(k)}(t) = \sqrt{2P_2} \cdot P^{(k)}(t) \cdot D^{(k)}(t) \cdot \sin(2\pi f_{L2}t + \theta_{L2})
\]  

(3.2)

where \( P_c, P_1 \) are the signal powers for L1 signals; \( P_2 \) is the signal power for L2 signals; \( C^{(k)} \) and \( P^{(k)} \) are the C/A code and P(Y) code sequences assigned to the satellite number \( k \); \( D^{(k)} \) are the satellite navigation data bit stream; \( f_{L1} \) and \( f_{L2} \) are the carrier center frequencies corresponding to L1 and L2 respectively; \( \theta_{L1} \) and \( \theta_{L2} \) are the phase offsets for L1 and L2 signals respectively [15].

The general expression for L2C signal is given by:

\[
 s_{L2C}^{(k)}(t) = \sqrt{2P_{c2}} \cdot D_{c2}^{(k)}(t) \cdot CM^{(k)}(t) \cdot \cos(2\pi f_{L2}t + \theta_{L2}), \quad nT_{c2} < t \leq (n+1/2)T_{c2}
\]  

(3.3)

\[
 s_{L2C}^{(k)}(t) = \sqrt{2P_{c2}} \cdot C^{(k)}(t) \cdot \cos(2\pi f_{L2}t + \theta_{L2}), \quad (n+1/2)T_{c2} < t \leq (n+1)T_{c2}
\]  

(3.4)

Where CM is the moderate-length code for the \( k^{th} \) satellite; CL is the long code for \( k^{th} \) satellite; \( T_{c2} \) is the chip width; the superscript (k) indicates the \( k^{th} \) satellite. The new L2C signal generation is shown in Fig.3.2.
The general expression for L5 signal is given by:

\[
s(t) = \sqrt{2P_{L5}[D_{L5}(t) * XI(t) * NH_{10}(t) * \cos(2\pi (f_{L5} + f_d) * t + \theta_{L5}) + XQ(t) * NH_{20}(t) * \sin(2\pi (f_{L5} + f_d) * t + \theta_{L5})]}
\]  \hspace{1cm} (3.5)

where \( P_{L5} \) is the total power of the received GPS L5 signal, \( D(t) \) is the binary Non-Return to Zero (NRZ) navigation message, \( XI(t) \) and \( XQ(t) \) are the binary PRN code, \( NH_{10} \) and \( NH_{20} \) are the 10-bit and 20-bit Neuman-Hoffman (NH) code respectively, \( f_{L5} \) is the L5 carrier frequency, \( f_d \) is the Doppler frequency due to the relative motion between the satellite and the receiver, \( \theta_{L5} \) is the carrier phase delay. Fig.3.3 shows the block diagram for the GPS L5 signal generation.

![Fig.3.3. Block Diagram of GPS L5 Signal Generation](image)

![Fig.3.4. Block Schematic Diagram of GLONASS Signal Generation](image)
3.1.2. GLONASS Signal Generation

Unlike the GPS signals that use code division multiple access (CDMA) modulations, the GLONASS signals use frequency division multiple access (FDMA) modulation, where each satellite transmits its carrier signal on its own sub-band with 0.5625-MHz frequency offset on L1 and 0.4375-MHz frequency offset on L2.

\[
f_{k1} = 1.602GHz + k \times \Delta f_1, \quad \Delta f_1 = 0.5625MHz
\]
\[
f_{k2} = 1.246GHz + k \times \Delta f_2, \quad \Delta f_2 = 0.4375MHz
\]

Where, \( k \) is a frequency number (frequency channel) of the signals transmitted by GLONASS satellites in the L1 and L2 sub-bands. All GLONASS SVs launched after 2005 will use numbers of frequencies \( K = (-7...+6) \) [16].

Fig. 3.4 shows the diagram for the GLONASS signal generation [17]. The modulo-2 operation was carried out among the meander code, navigation data and PRN code. Then the modulo-2 result modulates onto the GLONASS L1 and L2 sub-carriers. The PRN code has a chipping rate of 511 KHz chips and 1 ms in period. The polynomial for generating the GLONASS PRN code is given as follows [16]:

\[
X = 1 + x^5 + x^9
\]  

(3.6)

3.2 GNSS Signal Playback System Performance Analysis

In order to verify the performance of the signal generator and playback system developed, several experiment cases were carried out. The GPS simulated signals for L1, L2C and L5 signal were used to test the performance of this playback system. The USRP-N210 and RFX1800 and RFX1200 daughter boards were used to transmit and receive the data. Besides the simulated GNSS data, we also used the real GNSS data to test the performance of this playback system.

Case 1: Transmit GPS L1 signal with daughter board RFX1800

We selected the GPS PRN18 satellite as the simulated signal with code sampling rate 5MHz and initial code phase at 500 sample points. The simulated Doppler frequency is 2.1 KHz. The carrier to noise ratio is 49dB-Hz. The acquisition plot of the simulated PRN18 is shown by Fig. 3.5.
The block schematic diagram of USRP-N210 transmission process is shown by Fig.3.6. The UHD environment is installed under Ubuntu 11.04 Linux operating system. The PC and USRP-N210 are connected with each other via the Gigabit Ethernet port. The transceiver daughter board RFX1800 is selected as the transmitting board for GPS L1 signal. We used the Agilent E4404B Spectrum Analyzer to monitor the transmitted signal.

An initialization process is needed to establish communication between the USRP-N210 and the hosting PC before configuration of some specific parameters of the transmitting command. The USRP-N210 can recognize three data types: double, float, and short. In this transmission experiment, we set the data type parameter as short, and the center frequency at 1.57542GHz, the data sample rate at 5MHz. The spectrum of the original data is shown in Fig.3.7 while the spectrum analyzer monitor result is shown as Fig.3.8. Visual inspection shows that the spectrum envelopes of the simulated data and transmitted data agree with each other.
Fig. 3.7. L1 CA Code Spectrum (PRN: 18, Sampling Rate 5MHz)

Fig. 3.8. Spectrum Analyzer Monitoring Result of GPS L1 Signal

Case 2: Transmit GPS L2C and L5 Signals with Daughter Board RFX1200

In this experiment case, the RFX1200 transceiver daughter board was used as the transmitter board. When transmitting L2C signal, we set the transmitting command parameter as follows: transmission carrier center frequency at 1.2276GHz, sample rate at 5MHz, data type as short.

Fig. 3.9. Input GPS L2C Code Spectrum (PRN: 1, Sampling Rate 5MHz)

Fig. 3.10. Spectrum Analyzer Monitoring Result of GPS L2C Signal
Fig. 3.9 and Fig. 3.10 are the spectrum of simulated input L2C signal data and the transmitted L2C signal via USRP-N210 respectively. According to the two spectrum envelope results, we can also come to the conclusion that they agree with each other very well.

Similarly, we transmitted GPS L5 signal via USRP-N210. The corresponding transmitting parameter that we set in this case is as follows: transmission carrier center frequency at 1.17645GHz, sample rate as 30MHz, data type as short.

![Spectrum Analyzer Monitor Result of L5 Signal](image)

Fig. 3.11 is the spectrum of simulated L5 data. Fig. 3.12 is the monitored spectrum of the transmitted L5 signal via USRP-N210. The two spectrum envelope results can also show that they agree with each other.

Although we did not conduct the experiments, other GNSS signals, such as GLONASS L1, L2, Galileo E1b, E1c, E5a, E5b, and Beidou signals should also be transmitted using the same setup.

**Case 3: USRP-N210 to USRP-N210 Transmitting and Receiving Experiment**

In this experiment case, we used two USRP-N210 units: one as the transmitter, the other as the receiver to receive the data transmitted from the transmitter. Each unit is controlled by a PC with Linux operating system.
Fig. 3.13 is a snapshot which shows the USRP-N210 to USRP-N210 transmitting and receiving system. Fig. 3.14 is the block schematic diagram of USRP-N210 to USRP-N210 transmitting and receiving process. Each USRP-N210 has the RFX1800 daughter board mounted on it. In the signal transmitting computer side, we set the transmitting parameters as follows: transmission carrier center frequency at 1.57542GHz, sample rate as 5MHz, data type as short. We choose the GPS L1 signal as the source data used in Case1. In the signal receiving computer side, we set the receiving parameters as follows: carrier center frequency at 1.57542GHz, sample rate at 5MHz, data type as short.

The spectrum of both the transmitted and received data are shown by Fig.3.15 and Fig.3.16 respectively. The spectral envelopes of the transmitted and received data are similar to each other.
Fig. 3.14. Block Schematic Diagram of USRP-N210 to USRP-N210 Transmitting and Receiving Process.

Fig. 3.15. Original L1 CA code Spectrum (PRN: 18, Sampling rate 5MHz)

Fig. 3.16 Playback L1 CA Code Spectrum (PRN: 18, Sampling rate 5MHz)
3.3 Real GNSS Data Playback via USRP-N210 and NovAtel Receiver

To further verify the performance of the playback system, we used the GNSS data received via a real GNSS front end as input for testing.

Fig. 3.17. Block Schematic Diagram of Playback System with USRP-N210 and NovAtel Receiver

This time, the real GPS L1 signal data was chosen as the transmitted source data with sampling rate 5MHz. Fig. 3.17 shows the block schematic diagram of playback system with USRP-N210 and NovAtel receiver. The personal computer1 (PC1) in the upper side of Fig. 3.17 acts as the controller which is used to control the USRP-N210. In the lower side of Fig. 3.17, the personal computer2 (PC2) is used as the monitor which can directly monitor the output result of the NovAtel receiver. The PC1 connects the USRP-N210 via the Ethernet port. The PC2 connects the NovAtel receiver via the serial port (RS-232).

Note that both the USRP-N210 and NovAtel receiver can output DC voltage, the DC block unit after the output of the USRP-N210 and before the input of the NovAtel receiver are needed to protect the units. Between the two DC blocks, we used 75 dB attenuator and a 1 meter cable.
line to connect the USRP-N210 and NovAtel receiver to ensure sufficient attenuation of the playback system output so that the NovAtel receiver input is not saturated. The snapshot of experimental setup is shown in Fig.3.18.

Software receiver algorithms are used to process the original data. Table 3.1 shows the $C/N_0$ computed by the software algorithms for the input signal and the Novatel receiver generated output signal-to-noise ratio (SNR). Notice that PRN 11 does not appeared in the sky-plot of the satellites monitored by NovAtel receiver and therefore does not have an entry of SNR value in the table. The software receiver calculation shows that PRN 11 has the smallest $C/N_0$ in the input and has a low elevation. All other 6 satellites successfully monitored by NovAtel receiver are all above 30-degree elevation angles, as shown in Fig.3.19. There are several possible reasons that PRN11 is not detected by the NovAtel receiver. One reason is that the USRP-N210 as a transmitter can also induce additional noise when transmitting the GNSS original data. Another reason is that the NovAtel receiver may have a threshold value for satellite carrier to noise ratio. For those low elevation angle satellites, if their $C/N_0$ value is below that threshold, the receiver will not show them as being successfully tracked.

![Fig.3.18. Snapshot of USRP-N210 and NovAtel Receiver in the Playback System](image-url)
Comparison of the absolute SNR for the input signal generated by our software algorithm and the CNR for the output signal generated by the NovAtel receiver can be misleading because they are two different quantities. Nevertheless, we can examine the relative differences in each set of results and see if any consistency exists between the two sets of data. We select PRN 12 as our reference satellite and compute the difference between other satellite and PRN 12. The results are also listed in Table 3.1.

Table 3.1 Results Processed by Software Receiver and NovAtel Receiver

<table>
<thead>
<tr>
<th>PRN</th>
<th>SNR (dB)</th>
<th>∆SNR (dB)</th>
<th>PRN</th>
<th>CNR (dB-Hz)</th>
<th>∆CNR (dB-Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>12.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>13.6</td>
<td></td>
<td>12</td>
<td>45.5</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>16.7</td>
<td>3.1</td>
<td>14</td>
<td>48.5</td>
<td>3.0</td>
</tr>
<tr>
<td>18</td>
<td>13.3</td>
<td>-0.3</td>
<td>18</td>
<td>46.6</td>
<td>1.1</td>
</tr>
<tr>
<td>22</td>
<td>18.6</td>
<td>5.0</td>
<td>22</td>
<td>50.4</td>
<td>4.9</td>
</tr>
<tr>
<td>25</td>
<td>13.9</td>
<td>0.3</td>
<td>25</td>
<td>47.2</td>
<td>1.7</td>
</tr>
<tr>
<td>31</td>
<td>13.7</td>
<td>0.1</td>
<td>31</td>
<td>47.1</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Several experiments cases with respect to signal transmitting and receiving were successfully carried out and described in the previous sections of this chapter. All these experiment results show that we can generate all GNSS signals controlled by a computer based on USRP-N210 paired with appropriate daughter boards (such as: RFX1800, RFX1200, etc.). The source of the
signals can be pre-recorded digital samples obtained from specific GNSS RF front end or arbitrary samples generated using MATLAB programs. The results in Table 3.1 show that the two sets of data are consistent with each other with about 1 dB fluctuations.

### 3.4 Reference Clock Effect Comparison

Reference clock plays a very important role in GNSS receiver measurement quality. Both TCXO and OCXO are used in testing the USRP-N210 playback performance comparison. The USRP-N210 mother board has an embedded TCXO. To achieve better GNSS signal tracking results, we also used an external OCXO to provide the reference clock for USRP-N210. The schematic block diagram with internal and external reference clock is shown by Fig.3.20. A two way clock splitter was used between USRP-N210 and TRIGR which provides the reference external OCXO clock.

In this experiment case, we mainly focused on analyzing the tracking performance of the signals recorded with external reference OCXO and the internal TCXO clock respectively for GPS PRN24, which simultaneously transmits GPS L1, L2C and L5 signals. The GPS L1, L2C, and L5 signals were recorded at 13:41:40 EST, 13:56:30 EST, and 14:01:13 EST on January 15, 2013 respectively. A 6th order Butterworth Filter with 0.1Hz cutoff frequency was used to detrend the carrier phase measurements in this paper. Fig.3.21 shows the comparison results of detrended carrier phase tracking measurements for L1, L2CM, and L5I recorded with internal TCXO and external OCXO reference clock for PRN24.

Fig.3.20. Block Schematic Diagram of External Reference Clock Synchronization for USRP-N210s Recording and Playback
Fig. 3.21. Detrended Carrier Phase Measurements of GPS L1, L2C and L5 Signals Recorded with External OCXO Clock and USRP-N210 Internal TCXO Clock respectively for PRN 24.

Fig. 3.22. Doppler Tracking Results Comparison between Recorded GPS L1 Signal with External OCXO Clock and USRP-N210 Internal TCXO Clock for PRN 24
Based on the results shown in Fig. 3.21, we can see that there is an obvious difference between the magnitudes of the detrended carrier phase measurements for all 3 signals. The comparison results of the Doppler tracking measurements using the two different clocks for GPS L1, L2C and L5 signals were shown by Fig. 3.22, Fig. 3.23 and Fig. 3.24 respectively for PRN24. Based on the results shown on these figures, we can see that the Doppler obtained using the TCXO not only shows much large variation compared to the results obtained with the external OCXO clock, it also shows a different Doppler trend despite the fact that the data is collected simultaneously.

![Fig. 3.23. Doppler Tracking Results Comparison between Recorded GPS L2C Signal with External OCXO Clock and USRP-N210 Internal TCXO Clock for PRN 24](image)

![Fig. 3.24. Doppler Tracking Results Comparison between Recorded GPS L5 Signal with External OCXO Clock and USRP-N210 Internal TCXO Clock for PRN 24](image)
The comparison results of the navigation data channel output measurements using the two different clocks for GPS L1, L2CM and L5I signals were shown by Fig.3.25, Fig.3.26 and Fig.3.27 respectively for PRN24. In Fig.3.25, the top figure shows the navigation data channel output for GPS L1 signals recorded with OCXO and TCXO respectively. The middle figure in Fig.3.25 shows the synchronized navigation data I channel output results from 5.0 seconds to 6.0 seconds for both GPS L1 signals recorded with OCXO and TCXO clock respectively. The bottom figure in Fig.3.25 shows that the navigation data still can be decoded correctly when recording the GPS L1 signal with OCXO clock from 18.0 to 19.0 seconds, but it can’t decode the navigation data with recording the signal with TCXO at that time range due to the tracking loop losing lock. The corresponding comparison results for GPS L2CM and L5I signals were shown by Fig.3.26 and Fig.3.27 respectively.

Fig.3.25. Navigation Data I Channel Output Tracking Results Comparison between Recorded GPS L1 Signal with External OCXO Clock and USRP-N210 Internal TCXO Clock for PRN 24
Fig. 3.26. Navigation Data I Channel Output Tracking Results Comparison between Recorded GPS L2C Signal with External OCXO Clock and USRP-N210 Internal TCXO Clock for PRN 24

Fig. 3.27. Navigation Data I Channel Output Tracking Results Comparison between Recorded GPS L5 Signal with External OCXO Clock and USRP-N210 Internal TCXO Clock for PRN 24
3.5 Tracking Measurements Performance Comparison

The tracking measurements performance comparison between recording and playback systems for GPS L1, L2C and L5 and GLONASS L1 and L2 signals will be demonstrated here. The RFX1800 and RFX1200 daughter boards were used to record and playback the GPS and GLONASS signals. Table 3.2 listed the daughter boards and the corresponding parameters values used in the signal recording and playback experiments. The GPS L1 and GLONASS L1 signals can be recorded and played back using RFX1800; and the corresponding bandwidth is set as 2.046MHz and 20.46MHz respectively. The center frequency is set to 1.57542GHz for GPS L1 and 1.5980625GHz for GLONASS L1. RFX1200 is used to receive GPS L2C, GPS L5 and GLONASS L2 signals with their corresponding center frequencies set to 1.2276GHz, 1.17645GHz and 1.2429375GHz, and bandwidths set to 2.046MHz, 20.46MHz and 20.46MHz respectively.

Table 3.2 Daughter boards setting for GNSS data recording and playback

<table>
<thead>
<tr>
<th>Daughter Boards Name</th>
<th>GNSS Type</th>
<th>Center Frequency(GHz)</th>
<th>Main Lobe Bandwidth (MHz)</th>
<th>Daughter Boards Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFX1800</td>
<td>GPS L1</td>
<td>1.57542</td>
<td>2.046</td>
<td>Transceiver</td>
</tr>
<tr>
<td></td>
<td>GLONASS L1</td>
<td>1.5980625</td>
<td>20.46</td>
<td></td>
</tr>
<tr>
<td>RFX1200</td>
<td>GPS L2C</td>
<td>1.2276</td>
<td>2.046</td>
<td>Transceiver</td>
</tr>
<tr>
<td></td>
<td>GPS L5</td>
<td>1.17645</td>
<td>20.46</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GLONASS L2</td>
<td>1.2429375</td>
<td>20.46</td>
<td></td>
</tr>
</tbody>
</table>

In the playback experiments, we set the attenuator to 60 dB between the two USRP-N210s. The TRIGR OCXO clock was used as the external reference clock. Four minutes of GPS L1, L2, and L5 data were collected at 19:58:32, 20:02:39, and 20:32:36 EST on Jan. 9, 2013 respectively, while four minutes of GLONASS L1 and L2 data were collected at 13:02:12 and 13:19:32 EST on Jan. 10, 2013 respectively. The sky plots of GPS and GLONASS satellites above the receiver location in Oxford, Ohio were shown by Fig.3.28 and Fig.3.29 respectively.
Example detrended GNSS carrier phase measurements comparison between original and playback signals for GPS L1, L2CM and L5I are shown by Fig.3.30 for PRN25. The corresponding scatter plot of navigation data comparison between original and playback signals.
for GPS PRN25 are shown by Fig.3.31. The figures show that the detrended carrier phase for
GPS L2C original signal varies more than its corresponding playback signal, which is an
exception in this experiment. The scatter plot of navigation data shown by Fig.3.31 indicates that
the navigation data scatters over a smaller area and closer to the origin for playback signals
compared to that of the original recorded signal. This indicates loss of some energy in the signal
channel during the playback process. The comparison between detrended carrier phase
measurements and scatter plot of navigation data for both GLONASS L1 and L2 signals are
shown in Fig.3.32 and Fig.3.33 respectively. In this experiment case, we studied the frequency
channel -2 for both GLONASS L1 and L2 signals. Similar observations can also be observed for
the GLONASS signals. Comparison of the mean and standard deviations of C/N₀ for GPS and
GLONASS based on the software tracking algorithms between the original recorded GNSS data
and playback data were shown by Fig.3.34 and Fig.3.35 respectively; and the numerical results
are listed in Table 3.3. The results show that the average and variations of C/N₀ values and the
carrier phase noises are very similar between the original data and the playback signal for both
narrowband and wideband signals.

![Fig.3.30. Detrended GPS L1, L2C and L5 Carrier Phase Measurements Comparison between Original and Playback Signals for PRN25](image-url)
Fig. 3.31. Scatter Plot of Navigation Data Comparison between Original and Playback Signals for GPS PRN25

Fig. 3.32. Detrended GLONASS L1 & L2 Carrier Phase Measurement Comparison between Original and Playback Signals for Channel -2
Fig. 3.33. Scatter Plot of Navigation Data Comparison between Original and Playback Signals for GLONASS FCH -2

Fig. 3.34. Tracking results Comparison between Original Recorded GPS Data and Playback Data with Respect to CNR, Standard Deviation of both CNR and Detrended Carrier Phase Measurements (the PRN numbers which less or equal than 32 represent the GPS L1 PRNs; L2-1, L2-12, L2-25, L2-29 and L2-31 represent GPS L2CM Code for PRN1, PRN12, PRN25, PRN29, PRN31 respectively; L5-1 and L5-25 represent GPS L5I code for PRN1 and PRN25 respectively)
Fig. 3.35. Tracking results Comparison between Original Recorded GLONASS Data and Playback Data with Respect to CNR, Standard Deviation of both CNR and Detrended Carrier Phase Measurements (the G1-3, G1-2, G1-n1, G1-n2, G1-n3, G1-n4, G1-n5 and G1-n6 represent GLONASS L1 frequency channels 3, 2, -1, -2, -3, -4, -5, -6 respectively; the G2-3, G2-2, G2-n1, G2-n2, G2-n3, G2-n4, G2-n5 and G2-n6 represent GLONASS L2 frequency channels 3, 2, -1, -2, -3, -4, -5, -6 respectively)
Table 3.3 Summary of signal tracking results between original and playback GNSS signals

<table>
<thead>
<tr>
<th>Signal Type</th>
<th>PRN</th>
<th>Original GNSS Signal</th>
<th>Playback GNSS Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C/N&lt;sub&gt;o&lt;/sub&gt; (dB-Hz)</td>
<td>C/N&lt;sub&gt;o&lt;/sub&gt; (dB)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Standard Deviation</td>
<td>Carrier Phase Φ (rad)</td>
</tr>
<tr>
<td>GPS L1&lt;sup&gt;1&lt;/sup&gt;</td>
<td>1</td>
<td>39.4</td>
<td>0.206</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>34.7</td>
<td>0.451</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>38.6</td>
<td>0.369</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>44.1</td>
<td>0.192</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>34.2</td>
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</tr>
<tr>
<td></td>
<td>20</td>
<td>40.1</td>
<td>0.182</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>41.1</td>
<td>0.604</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>42.5</td>
<td>0.176</td>
</tr>
<tr>
<td></td>
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<td>29.9</td>
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<td>41.2</td>
<td>0.580</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>47.5</td>
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<tr>
<td></td>
<td>32</td>
<td>46.5</td>
<td>0.173</td>
</tr>
<tr>
<td>GPS L2C&lt;sup&gt;2&lt;/sup&gt;</td>
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<td>36.0</td>
<td>0.115</td>
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<tr>
<td></td>
<td>12</td>
<td>33.2</td>
<td>0.164</td>
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<tr>
<td></td>
<td>25</td>
<td>38.2</td>
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<tr>
<td></td>
<td>29</td>
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<td>0.157</td>
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<td></td>
<td>31</td>
<td>41.7</td>
<td>0.212</td>
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<tr>
<td>GPS L5&lt;sup&gt;3&lt;/sup&gt;</td>
<td>1</td>
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<td>25</td>
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<td>0.111</td>
</tr>
<tr>
<td>GLONASS L1&lt;sup&gt;4&lt;/sup&gt;</td>
<td>3</td>
<td>29.2</td>
<td>0.195</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>35.9</td>
<td>0.215</td>
</tr>
<tr>
<td></td>
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<td>40.2</td>
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<td>0.533</td>
</tr>
<tr>
<td></td>
<td>-6</td>
<td>38.9</td>
<td>0.174</td>
</tr>
<tr>
<td>GLONASS L2&lt;sup&gt;5&lt;/sup&gt;</td>
<td>3</td>
<td>30.9</td>
<td>0.206</td>
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<td></td>
<td>2</td>
<td>34.8</td>
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<td>34.5</td>
<td>0.110</td>
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<tr>
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<td>-2</td>
<td>34.8</td>
<td>0.162</td>
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<td>38.9</td>
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<td>0.341</td>
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<td></td>
<td>-5</td>
<td>28.4</td>
<td>0.322</td>
</tr>
<tr>
<td></td>
<td>-6</td>
<td>34.7</td>
<td>0.153</td>
</tr>
</tbody>
</table>

<sup>1</sup>GPS L1 Data Collected for about 4 minutes in length on Jan. 9, 2013, 19:58:32 PM EST at Software Receiver Lab, Miami University.

<sup>2</sup>GPS L2C Data Collected for about 4 minutes in length on Jan. 9, 2013, 20:02:39 PM EST at Software Receiver Lab, Miami University.

<sup>3</sup>GPS L5 Data Collected for about 4 minutes in length on Jan. 9, 2013, 20:32:36 PM EST at Software Receiver Lab, Miami University.

<sup>4</sup>GLONASS L1 Data Collected for about 4 minutes in length on Jan. 10, 2013, 13:02:12 PM EST at Software Receiver Lab, Miami University.

<sup>5</sup>GLONASS L2 Data Collected for about 4 minutes in length on Jan. 10, 2013, 13:19:32 PM EST at Software Receiver Lab, Miami University.
3.6 Playback System Positioning Performance Comparison

This section will focus on the positioning performance comparison between the original recorded and playback GPS L1 signal to further demonstrate the playback performance via USRP-N210 instrument.

We used the positioning results that calculated by Septentrio commercial receiver as the reference antenna position when we record the GPS L1 signal via the same antenna. The antenna’s position calculated via Septentrio commercial receiver in GEO coordinate is:

- Latitude: $39^\circ30'38.2933''$
- Longitude: $-84^\circ43'55.9647''$
- Altitude: $269.8\pm3.5m$

The software receiver processing results in GEO coordinate is:

- Latitude: $39^\circ30'38.6296''$
- Longitude: $-84^\circ43'56.2348''$
- Altitude: $261.6\pm69.2m$

The Universal Transverse Mercator (UTM) geographic coordinate system uses a 2-D Cartesian coordinate system to give locations on the surface of the earth. It is a horizontal position representation, i.e. it is used to identify locations on the earth independently of vertical position, but differs from the traditional method of latitude and longitude in several respects [18]. The positioning performance comparison results that represented in UTM coordinate are shown by both Fig.3.36 and Fig.3.37.

In Fig.3.36, we can see that the red dots located in the center of this figure represent the averaged antenna position calculated by the Septentrio commercial receiver. The blue area shown in the figure represents the east and north positions that calculated by Septentrio commercial receiver. The green dots in the figure represent the east and north position that generated by the software receiver for the playback data. The red stars in the figure represents the east and north position generated by the software receiver for the original recorded signal. Through comparison, we can see that the east and north position results that calculated by software receiver for both recorded and playback signals spread at the same level. The corresponding position results for altitude of the antenna were shown by Fig.3.37.
Fig. 3.36 East and North Positions in UTM System

Fig. 3.37 Height in UTM System
3.7 Summary

In this chapter, both the real and simulated GNSS signals were successfully processed by the USRP-N210 based playback system. GPS L1, L2C, L5, and GLONASS signal generation structure characteristics were summarized, and the real GNSS signal collection system in Miami University is also introduced in this project. The performance comparison between the original recorded and playback signals were demonstrated. The reference clock effect was also introduced. The comparison with respect to positioning results in relevant to original recorded and playback signals was introduced at the end of this chapter. The positioning results that calculated via the program that modified from the source code in [19].
Chapter 4

User API Development under UHD Environment

In this Chapter, the Multi-core and Multi-threads programming techniques will be introduced to solve the overflow and underflow problems that we encountered when we use the USRP-N210 products to record or play back the GNSS signals.

4.1 UHD Environment and Overflow and Underflow Problem

UHD software is the "Universal Software Radio Peripheral" Hardware Driver software [20], which is the official hardware driver for USRP-N210. It was developed using C++ language. The goal of UHD software is to provide a host driver and API for current and future Ettus Research products. Users will be able to use the UHD driver in standalone mode or with third-party applications. The functions of the sample program that accompanied the USRP-N210 are very limited. In order to satisfy the user’s specific need, the sample program code that provided by UHD programming environment needs to be modified.

The overflow and underflow problems may occur when the USRP-N210 is used to record or play back wideband GNSS signals. Since the data saving speed of personal computer’s hard drive is not fast enough, the overflow problem may occur when we record the wideband GNSS signals with high sampling speed. The underflow problem often occurs when we play back wideband GNSS signals with high data sampling rate.

4.2 Underflow and Overflow Handling

In order to solve the overflow or underflow problems, the sample program that provided by the UHD environment should be modified according to our specific requirement.

The schematic block diagram of original UHD sample program code for data transmission is shown by Fig.4.1. There is just one thread (thread 0 shown by Fig.4.1) used in the original sample program provided by UHD environment. The thread 0 will first extract data from local computer hard drive and then send the data directly to USRP-210 for transmitting purpose. Since the USRP-N210 needs some time to transmit all data, the program’s main thread will be idle and
wait for the next data extraction command from USRP-N210. Valuable CPU resource will be wasted when the main program thread is idle. When the USRP-N210 transmits high speed sampling data, the program’s main thread should have the ability to extract more data from computer hard drive each time. Currently, the data reading speed will limit the hard drive to provide enough data for USRP-N210 to transmit each time. So, when we use the original sample program code to playback the wideband GNSS signals, the underflow problem may occur.

![Schematic Block Diagram of UHD Sample Program for Data Transmission](image)

**Fig.4.1** Schematic Block Diagram of UHD Sample Program for Data Transmission

State-of-the-art personal computer has 2, 4, or even more CPU cores. In order to solve the underflow problem, we should fully take advantage of the CPU resources to provide enough data for the USRP-N210 to transmit. Compared with using just one thread to process the data in the original sample program, modified sample code with multi-threads programming techniques will improve the performance of the playback system. As is the so called multi-core and multi-thread programming ideas.

Fig.4.2 shows the schematic block diagram of modified data transmission program with the multi-threads approach. In order to solve the underflow problem, we keep the original main thread (thread 0), and added two slave threads into the original sample program code (Slave thread 1 and thread 2 which were shown by Fig.4.2).
Slave thread 1 extracts data from the PC hard drive and then put them into the user defined Memory Data Array shown inside the red dashed line in Fig.4.2, which is also the so called shared memory area [21, 22, 23, 24, 25]. The pseudo-codes to explain the function of slave thread 1 is shown below:

**Thread 1:**

```cpp
std::queue dataArray;  // Define dataArray queue
std::ifstream dataFile(fileName);  // Define input file stream
while (!dataFile.eof()) {
    dataFile.read(charArray,num);  // Get data from the file and save them into charArray
    dataArray.push(charArray);  // Push the charArray into dataArray queue
}
```

Fig.4.2 Schematic Block Diagram of Modified Data Transmission Program with Multi-threads
Caution should be taken when using multi-threads to process the shared memory area since race problem may occur between two threads [26]. Program code in this thread will always determine if the user defined memory is full or not. If the memory is full, the thread will be idle. Otherwise, it will continuously extract data from the PC hard drive and write the data into the Memory Data Array.

Slave thread 2 will get data from the user defined memory and sent it to USRP-N210 for transmitting. The pseudo-codes to explain the function of slave thread 2 is shown as below:

**Thread 2:**

```java
while(!(dataArray.empty())) { // Determine if the dataArray queue is empty
data = dataArray.front(); // Get data from dataArray queue
dataArray.pop(); // Delete the old data from dataArray
USRP_Transmit(data,data.length()); // USRP-N210 will transmit the data out
}
```

The multi-threads based program modification approach will correct the underflow problem when we use USRP-N210 to play back the wideband GNSS signals. If we have additional data processing requirements, we can define another memory area, and add more threads to process it. The multi-threads programming technique can be very convenient for us to modify the sample program to fulfill our own specific requirements [26, 27].
Chapter 5
Conclusions and Future Works

5.1 Conclusions

A reconfigurable wideband multi-frequency multi-constellation GNSS signal recording and playback system based on the Universal Software Radio Peripheral (USRP) N210 model had been demonstrated in details in this thesis.

The widespread application and utility of the GNSS systems, such as GPS, GLONASS, GALILEO, BEIDOU, etc., has led to a new era of growth in satellite-based navigation technologies. GNSS and applications, however, face many challenges. GNSS signals are commonly subjected to both manmade and natural interferences such as RF jamming, ionosphere scintillations, multipath, signal degradation under bridges or blocked by foliage, and signal anomaly, etc. In order to achieve the desired navigation application performance, advanced receiver processing or multi-sensor integration algorithms must be developed to mitigate these interferences. A flexible multi-frequency multi-constellation GNSS signal generator is an important enabler of robust GNSS receiver research and development.

Based on all the experiment results shown in this thesis, we can see that the reference clock plays a very important role when we use the USRP as recording or playback tools. If we want to record high quality GNSS and playback it with USRP, we should use an external OCXO clock instead of the USRP internal TCXO clock. The C/N0 value, carrier phase error standard deviations between original recorded signal and playback measurements were comparable, which were shown in details in Chapter 3.

All the experiments summarized in this thesis were carried out at the Software Receiver Lab at Miami University. The receiver output and the transmitted signal are processed by both NovAtel and software receivers and compared with the original signal parameters to demonstrate the accuracy of the playback system. Additionally, the solutions for solving the overflow and underflow problems that we encountered when we use the USRP-N210 as signal recording and playback system had also been introduced in Chapter 4.
Although there are some existing materials which can enrich this thesis, it did not spend long paragraph to repeat it herein, such as the basic signal generation and processing principle for the GALILEO and BEIDOU signals. The signal structure and generation for both GALILEO and BEIDOU can be referenced to the corresponding ICDs [4, 28]. The basic GNSS signal acquisition and tracking principle can be referenced to the classic text books [12, 14, 15]. The FLL assisted with PLL principle for high dynamic GNSS signal acquisition and tracking can be referenced to [29]. The high sensitivity GNSS signal processing techniques that used for weak signal acquisition and tracking can be reference to [12]. The pseudo-range extraction, SVs’ position and user’s position calculation can be referenced to [19].

5.2 Future Works

Current research works focused on the performance analysis of GNSS signals that collected in open sky in static environment. The performance comparison results indicate that the USRP-N210 based signal recording and playback system can be used as an efficient tool for developing and verifying the advanced GNSS signal processing algorithms. The future works has been extended to include the following several topics.

5.2.1 High Performance Computing Testing

In industry field, the hard drive’s reading and writing speed puzzled hardware engineers all the times. They tried to upgrade the hard drive’s performance time and time again. Compared with the original phase, the hard drive’s reading and writing speed has been improved much more than before. However, in academic researching field, it still can’t satisfy their data reading and writing speed requirements for academic experiments. Due to the speed limit in reality, they need to find other ways to solve the data reading and writing speed problem.

In this project, in order to solve the underflow problem when we use USRP-n210 to playback wideband GNSS signals, I modified the source code that provided by UHD environment and the code modification structure was shown in Chapter 4. I used two slave threads to read and send data simultaneously to improve the USRP’s data reading speed efficiency. Since the computer server, which we used to record and playback GNSS signals in Software Receiver Lab at Miami University, was moved to Ascension Island for another project, the modified source code can’t be tested at that time before my final thesis defense. The future works about testing the modified
code based on multi-threads ideas belongs to high performance computing field, which will include two part contents.

- **Static Data Transmitting Mode**

In this test case, the data which will be used to playback with USRP-N210 will first be moved from local hard drive into memory. Due to the memory size limit, we should make sure the available memory size first before playing back data under this mode. Fig.5.1 shows the schematic block diagram structure of testing the modified source code based on multi-threads ideas under static data transmitting mode. Through Fig.5.1, we can see that the user should first estimate the data size which will be moved from local hard drive into memory. Then specify the time length which can be used to calculate the data size that used to playback with USRP-N210.

![Fig.5.1 Schematic Block Diagram of Static Data Transmitting Mode](image-url)
• **Real-time Data Transmitting Mode**

In this test case, we don’t need to wait for long time to move all the data into memory in the first step. The two slave threads will work simultaneously without any conflict about reading data from the memory or writing data into memory. Fig. 5.2 shows the schematic block diagram of real-time data transmitting mode.

![Schematic Block Diagram of Real-time Data Transmitting Mode](image)

Although it can save us some time, it is much more challenging when we only use the real-time data transmitting mode alone. In order to keep the playback system work fluently, we’d better to combine the two testing mode together, which means we can first wait for some short time to move the data from local hard drive into memory and then start the two slave threads together.

**5.2.2 Non-Open Sky Environments**

The works shown in this thesis mainly focused open-sky environment. The future works will be extended to the non-open sky environments which will include the following cases.
• Bridge Case

When in bridge case, the challenge for GNSS receiver is that most of useful satellites’ signal will be deteriorated and becomes very weak when receiver was under the bridge. The deteriorated satellite signals will induce large pseudo-range error which will affect the user’s position calculation. The system presented in this thesis can record and playback the signals in such environment and develop the corresponding advanced signal processing algorithms to mitigate the user’s position calculation error when the receiver was under the bridge.

• City Canyon Case

When in city canyon case, the big challenge for receiver is multipath. Strong satellite signals may be blocked or reflected by high buildings. Sometimes, the total number of acquired satellites is less than 4 when receiver working in city canyon environment for one single GNSS constellation, such as GPS, or GLONASS, etc. So, the playback system presented in this thesis can record and playback the GNSS signals under such environment. It can be useful to develop advanced multi-GNSS combining receiver algorithms which can improve the total number of useful acquired GNSS satellites for multi-GNSS constellations in city canyon environment.

5.2.3 Array Antenna Signal Processing

The system presented in this thesis can also be used to collect and playback array antenna signals for advanced GNSS signal anti-jamming algorithm development. The schematic diagram of array antenna signal processing via USRP-N210s is shown by Fig.5.3. Through Fig.5.3, we can see that there are four antenna elements equally distributed along a circle with radius r, and one element distributed at the center of the circle. The GNSS signals will first impinge on the array antennas, and then collected via USRP-N210s array. Followed by the signal anti-jamming algorithm processing block, where the jammer signals will be removed through the corresponding algorithms. The jammer removed GNSS signal will further be processed by software receiver, and the P.V.T (Position, Velocity, Time) calculation results will be provided by software receiver.
5.3 Summary

The USRP is a powerful tool, which can help both academic and engineering researchers to develop the corresponding advanced algorithms to solve the problems that they encountered in reality world. The application of USRP has been extended to many fields, such as satellite navigation, radar, digital signal processing, wireless communication, etc. The work shown in this thesis is just the initial step on how to use USRP-N210 series products to record and playback the GNSS signals. Much more works are left to the readers who are interested about developing advanced algorithms via USRP series products.
**Bibliography**


