SIMULINK® BASED MODELING OF A MULTI GLOBAL NAVIGATION SATELLITE SYSTEM

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The objective of this thesis is to design a model for a multi global navigation satellite system using Simulink. It explains a design procedure which includes the models for transmitter and receiver for two different navigation systems. To overcome the problem, where less number of satellites are visible to determine location degrades the performance of any positioning system significantly, this research has done to make use of multi GNSS satellite signals in one navigation receiver.
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1.1. Motivation

The global positioning system (GPS) is playing a vital role in the present world. As technology progresses the advancement and complexity in GPS devices is growing [37]. GPS technology is now being used everywhere, from mobile phones, watches, train stations to banks and ATM’s. Increase in use of GPS helps in improving the economy, including construction, mail delivery, farming, mining, and health care [38]. GPS is now a part of our lives, without which most of the present wireless services cannot work [42]. It is also responsible for many advancements in science such as weather forecasting, early detection of natural hazards and environmental protection. Finally, GPS remains an important component of the US national security. Many military devices come equipped with GPS. The inventions on GPS are still taking place and the future of GPS is only limited by human imagination.

The Indian Regional Navigation Satellite System (IRNSS) which is operated by the Indian Space Research Organization (ISRO) has seven satellites. Three of those satellites are in GEO (geostationary earth orbit) and four are in GSO (geosynchronous orbit). All these satellites have been launched successfully and will be operational very soon. These seven satellites cover most of the Asian continent and ISRO aims at making it global in the coming years. This global navigation satellite system (GNSS) gives more accurate positioning than GPS because it has two band frequencies, one in the L5 and the other in the S bands. These two band frequencies help dual channel receivers in finding atmospheric effects to determine the exact location. Once the IRNSS is operational, it will create more accurate locations in Asian countries, which further helps in many applications.

During the last decade, a few countries have started designing their own navigation systems for greater accuracy. This also decreases their dependency on other countries’ navigation systems.
Some countries have already completed their navigation systems successfully while others are still progressing towards it. For example, GLONASS from Russia became fully operational in 2011 [6]. Recently, on April 28, 2016, the Indian government launched its last satellite namely IRNSS-1G [8]. Some of these navigation systems are regional satellite navigation systems and some other are global satellite navigation systems. These individual navigation system signals, when combined in the navigation receiver at the user end, increase the speed and accuracy of location determination. With little increase in hardware complexity, the performance of the receivers can be improved greatly.

In this thesis a Simulink® model for a Multi Global Navigation Satellite System (GNSS) is designed to explore the performance when multiple navigation systems are combined for location determination. Two such navigation systems are used. One is the global satellite navigation system ‘GPS’ and the other is the regional satellite navigation system ‘IRNSS’. Both GPS and IRNSS systems consist of three basic components. They are: 1) Satellites, 2) Control Stations and 3) Receivers. There are a minimum of 24 active satellites for GPS and 7 active satellites for IRNSS in space. All these satellites have 3 components: Transmitter, Control station and Receiver. The transmitter sends signals to the ground while control stations at the ground are responsible for monitoring these satellites. The last component, the receiver, is present at the user end. These receivers are present in GPS-enabled electronic devices and are getting smarter as time progresses. Research on the receiver end is active, and researchers are trying to make these devices portable, more accurate, with lower power consumption [37]. Software Defined Receivers (SDR) are becoming popular because of their flexibility, modularity, and ease of upgrading [32]. Multi GNSS receivers are easily designed in software, which makes the graphical approach a natural choice for implementation. With this motivation the design is done in Simulink® [20].

1.2. Satellite Navigation

The Global Navigation Satellite System (GNSS) represents a satellite navigation system with global coverage. In satellite navigation, the receiver at the ground receives signals from
multiple satellites and uses the concept of triangulation to find its position, velocity, and other positional data. But the precision in finding the location varies depending on the type of technology used. For example, SA (Selective Availability) is the intentional degradation of GPS signals by the DoD, which causes accuracy to be limited to 100 meters. This was turned off by US president Bill Clinton in May 2000 to make GPS more responsive to civil and commercial users worldwide. For the precise positioning service (PPS) which is used in military applications, accuracy is limited to 1 meter only. In the same way IRNSS also has two services: one is for civilian users, called Standard Position service and the other is for authorized users, called restricted service (RS). Different types of satellite navigation systems are discussed below.

1.2.1. Global Positioning System (GPS)

GPS is a US owned navigation system using timing and ranging (NAVSTAR), with 24 satellites. This system consists of three segments: the space segment, the control segment, and the user segment. The US Air Force improves, keeps and controls the space and control segments. The user segment is the GPS receiver that is present at the end-user side [7]. GPS was invented with primarily military applications in mind. In the 1980s GPS was made available for public use in general purpose applications. GPS works anywhere, anytime and is free. No subscription or setup is needed [37].

The GPS space segment consists of a satellite constellation, transmitting the radio signals to the users. The US is committed to provide at least 24 of active satellites over 95% of the time. To achieve this, the US Air Force has been flying 31 operational satellites over the years. These satellites in the space segment fly in medium Earth orbits with an altitude of 20,200 km (12,550 miles) and they revolve around the earth twice a day with orbit period of 12 hours. To ensure that users see at least four satellites at any time, these 24 satellites are placed in six different orbital planes with four satellites in each plane. If any of these satellites is not working properly, extra satellites help to maintain the coverage. These extra satellites are helpful in increasing performance only and are not part of the core constellation. The satellites in the constellation are not launched
Figure 1.1. GPS Constellation, after [1].

A GPS constellation includes a mix of old and new satellites. Figure 1.1 shows the location of satellites in a constellation [1].

The GPS control segment consists of a global network of facilities that can receive the GPS signals and process them to analyze its performance. Based on the performance, this segment sends commands and data to the constellation. The present operational control segments are: one master control station (MCS), one alternate master control station, 12 command and control antennas and 16 Monitoring Sites. Figure 1.2 shows locations of different control segments present on the earth [2]. The master control station in the control segment is located in Colorado and provides primary control functions giving commands to the constellation. The health and accuracy of the constellation is continuously monitored by this MCS. Other control segments help MCS in this process.

The user segment is present at the user end in the GPS receiver. This receives the GPS
signal and calculates the location of the user with simple geometry. These GPS receivers are being developed over time to improve accuracy and reduce the time taken to do calculations.

1.2.2. Global Navigation Satellite System (GLONASS)

GLONASS is a global satellite navigation system operated by the Russian Aerospace Defense Forces with 24 satellites. The satellites in GLONASS orbit the earth in three orbital planes separated by an angle of 120° and with an altitude of 19,140 Km. The satellites in this GNSS also orbit the Earth almost twice a day with an orbital period of 11 hours 15 minutes. Eight satellites for each plane are equally spaced at an angle of 45° and identified by slot number, which defines the corresponding orbital plane and its location within the plane [6].
1.2.3. Galileo (In Development)

Galileo is a global satellite navigation system which is being developed by the European Union and the European Space Agency. It consists of 30 satellites, expected to be completed by 2019. Europe has estimated that, if the GPS signal is lost for two days, the transport sector alone loses 220 million €. For this reason the Galileo mission was started. In 2005, the first satellite was launched and as of December 2015 this GNSS has 12 of 30 satellites in orbit [5]. In the future, the integrated GPS-Galileo Navigation Satellite System will expand its applications in many fields [16].

1.2.4. Compass (In Development)

Compass is a global satellite navigation system presently being developed by China which consists of 35 satellites, expected to be completed by 2020. It is the second generation for China’s regional BeiDou satellite navigation system, and for this reason Compass is also called BeiDou-2. BeiDou is a regional satellite navigation system which has only three satellites and provides limited coverage and applications [4]. Compass or BeiDou-2 are capable of providing continuous, real time passive 3D geo-spatial position and speed measurement. One key advantage of BeiDou is the low service cost in marine positioning and communication services. The compatibility of GPS L1 and COMPASS B1 signals will offer users more accurate positioning results [34].

1.2.5. Indian Regional Navigational Satellite System (IRNSS)

IRNSS is India’s independent regional satellite navigation system, being developed by the Indian Space Research Organization (ISRO) [8]. The operational name for this navigation system is NAVIC. IRNSS is intended to provide an all-weather absolute position accuracy of better than 7.6 meters throughout India and within a region extending approximately 1,500 km around it. The IRNSS satellite navigation mission has been started by India because in hostile situations foreign government-controlled GNSS is not guaranteed. NAVIC has two services namely, Standard Positioning Service open for civilian use, and the Restricted Service for authorized users.
An IRNSS constellation consists of seven satellites. A few IRNSS applications are terrestrial, aerial and marine navigation, disaster management, environmental protection, vehicle tracking and fleet management.

1.2.6. Multi GNSS Satellite Navigation

The Global Navigation Satellite System (GNSS) is a constellation of satellites in space and provides global coverage with positioning and timing data [30]. As stated earlier, there are different GNSSs, operated by different countries. Few of them are currently in working condition and others are being developed. GPS and GLONASS are currently available to users in multi GNSS receivers. IRNSS is being developed by India. The seven satellite constellation was launched recently and will provide signals to users very soon. Simulation of any GNSS system and reception on these signals can be done once the signal characteristics are known. Some experiments are done in this area to test the signal generation and reception capabilities for new GNSS signals [29, 46].

A GNSS architecture is divided into three major segments: Space Segment (SS), Ground Segment (CS), and User Segment (US) for all satellite navigation systems. The space segment transmits radio-navigation signals with defined signal structure, whereas the ground segment is responsible for proper operation of the navigation system. The user segment is present in GNSS receivers and its function is to receive the signal and process it to find the user location. The introduction of new GNSSs leads to the necessity in designing multi-GNSS receivers that can be reconfigured across GNSS signals [48].

1.3. Project Management

The project is to design and implement a GNSS navigation system in Simulink®. The design has two parts: 1) Transmitter and 2) Receiver. The transmitter in real life is present in satellites and sends signals to the ground. There are 24 active satellites in GPS and 7 satellites in
IRNSS which send signals continuously.

The project design covers both GPS and IRNSS navigation systems. In the transmitter part, there are two modules, one is to generate the GPS L1 signal and the other is to generate the IRNSS L5 signal. These signal generation and modulation schemes are explained in detail in further chapters. Additive White Gaussian Noise (AWGN) with adjustable noise variance, Rayleigh and Rician channel models are considered for the performance analysis. The receiver part also consists of two different modules, one to acquire the GPS L1 signal and the other to acquire the IRNSS L5 signal. The project is divided into two parts. One part is to design the GPS and IRNSS transmitters and the other is to design the receiver. This receiver can acquire satellites and extract navigation data from the received signal. Figure 1.3 shows the work breakdown for the project implementation.

1.4. Choice of Tool

Simulink® is a product of Matlab® which helps to implement designs graphically [9, 28]. As the project requires the development of a program platform to test out the GNSS receiver structure, it is important to evaluate the various object programming languages for implementation.
Simulink® was chosen as the software to develop the GNSS navigation system. The main reason for the choice is that it has a very intuitive user interface combined with numerous features. Simulink® is a graphical environment which is able to make the relation between system modeling and simulation explicit. It is also an implementation cleaner and easier to debug because one can put test points anywhere and obtain immediate results [25]. Simulink® is incorporated with Matlab® [3], providing immediate access to a large range of tools that allow the development of algorithms and programs, the analysis and visualization of simulations with customizable set of block libraries, and the definition of signal, parameter, and test data.

1.5. Contributions of Thesis

Navigation and location determination is important for most applications, such as fleet management, rail-road transport, aviation, agriculture and many others. There is a need for design of new receivers that create applications to use multi GNSS signals in location determination. Also, with different countries designing their own navigation systems, the time for experiments and research on multi GNSS receiver design is here. With the recent successful launch of 7-satellite constellation by IRNSS and aim of ISRO to make it global soon, it is better to use it along with current global navigation system GPS. For these reasons this thesis is concentrated on the design of multi GNSS navigation system.

The overall objective of this thesis is to design a Simulink® based design and implementation of multi GNSS single channel dual frequency navigation system. As a part of thesis different navigation systems are being studied. Then the implementation of GPS and IRNSS transmitter design followed by the receiver is done in Simulink®. The channel environment is also created with three different models: Additive White Gaussian Noise (AWGN), Rayleigh and Rician.

The novel contributions of this thesis include the following:

- This thesis presents a unique design which uses the IRNSS navigation system along with GPS in improving location accuracy.
• Designed model characteristics are verified with different channel noise distributions which help in making the design more robust to work in any environment.
• Receiver design for both navigation systems with signal acquisition and navigation data extraction is presented.
• A study on different navigation systems and working principles is presented.
• This thesis simplifies the understanding of GPS or IRNSS technologies in the simulation flow.
• The design is done in Simulink®, as it has more scope to expand in the future. It can be exported to other systems like XILINX® in order to generate the actual hardware design in a Field Programmable Gate Array (FPGA).
• This thesis helps in incorporating other navigation systems in the present design to improve the location accuracy to a greater extent.

1.6. Outline of Thesis

This thesis is organized into five chapters. It discusses how a GNSS navigation system works and the different modules that affect its performance, i.e. location accuracy, power consumption and time. The history, development and applications of GPS are also studied. The rest of the thesis is organized as follows:

Chapter 2, GNSS Structure, briefly outlines some old navigation systems, signal structure, operation and performance of the GPS and IRNSS.

Chapter 3, Multi GNSS navigation system design in Simulink®, outlines the design of the basic GNSS navigation system in simulink®. This chapter also describes the function of all individual modules in detail.

Chapter 4, Observations and Analysis, describes the performance of the designed multi GNSS model based on several simulations and observations.

Finally, Chapter 5, Conclusions and Future Research, summarizes the conclusions and also presents future scope of this research.
CHAPTER 2

GNSS STRUCTURE

2.1. Background

Navigation is both an art and science which helps in getting from one place to another, safely and efficiently. In older days, people used sun light, stars and wind direction to travel from one place to other in oceans. They even used terrestrial landmarks by traveling near to shore. Navigation methods improved over the years and now we have satellite navigation systems for meter range accurate locations. Some early navigation systems that were used before satellite navigation are described in this section.

2.1.1. Loran Navigation System

LORAN stands for long range navigation and is a US developed hyperbolic radio navigation system which was used during World War II. Similarly, the UK used the Gee navigation system at the same time (Gee is the code name given to a radio navigation system used by the Royal Air Force). LORAN is operated at lower frequencies to provide navigation range up to 1500 miles. It uses pulsed radio transmission from master and slave stations. These are received on-board and recorded on CRT screens as small waves. The difference in time between arrivals of the signals from the two stations corresponds to the distance between the waves. These differences from multiple stations are represented as curves (hyperbolas) and the intersection of the two curves gives the location. This intersection is also called ‘LORAN lines of position’ [21].

It was used mainly by US ships, with an accuracy range of few kilometers. It was an expensive system with limited coverage and therefore used by the military and large commercial users. With developments in navigation technology, use of LORAN gradually decreased. There are some modified versions of LORAN system that are used for navigation called Loran-B and Loran-C. Loran-B was developed by the US Navy with an accuracy of tens of feet, but faced significant technical problems, whereas Loran-C is the other name for US Air Force ‘Cyclan’ [22].
2.1.2. Omega Navigation System

Before satellite navigation systems, the Omega Navigation System was used by the US in cooperation with six partner countries. It was developed by the US Navy for military aviation users and works with Very Low Frequency (VLF) radio signals in the range of 10 to 14 kHz. It was the first global range navigation system operational around 1971 and was shut down in 1997 with the increased use of GPS. For this system, the position tracking is also done with the help of three or more transmitters. Signals transmitted from the these transmitters helps receivers to find the location [31].

To understand the working principle of the Omega Navigation System, imagine a scenario where one ship is traveling at sea. Transmitters from the ground send same frequency signals and receiver in the ship receives these signals. When ship receives the signal from different transmitters, it first calculates the time difference and then the distance from the transmitter. With this information it can fix the position on a locus [35]. With the other transmitter signals the ship can then find its unique position on the map. With four or more transmitters the position is accurate. This ground navigation system has to use the Very Low Frequency (VLF) carriers, because they allow operation over large expanses of water with a minimum number of transmitting sites. For greater accuracy, typically 200 m, medium frequency carriers must be used which need many transmitters [41].

With these problems, to get more accuracy one cannot rely on ground navigation systems. To get an accuracy of less than 50 m, one will need to depend on satellite-based system. With this motivation GPS was invented by the US government for military positioning applications. In 1983, it was declared operational for usage by the civilian community [33]. The applications of GPS are increasing very fast, after it was allowed to be used by the civilian community. Some of the applications of GPS are road and rail transport, aviation, shipping, surveying, mapping and geophysics, etc.
2.2. Signal Structure

2.2.1. GPS Signal Structure

GPS satellite signals are low power radio signals. Two such signals are transmitted: L1 and L2. For general purpose applications we use L1, which has signal frequency of 1575.42 MHz. These signals transmitted by satellites are line of sight signals, i.e. they can pass through clouds, glass and plastic but not through most solid objects (buildings and mountains). Table 2.2.1 shows the characteristics of GPS signal structure for both L1 and L2 signals [23].

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Coarse/Acquisition (C/A) code</th>
<th>P(Y)-code</th>
<th>Navigation Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Chipping-rate)</td>
<td>1.023 MHz (Mbps)</td>
<td>10.23 MHz (Mbps)</td>
<td>50 Hz (bps)</td>
</tr>
<tr>
<td>Repetition</td>
<td>1 ms</td>
<td>1 week</td>
<td>N/A</td>
</tr>
<tr>
<td>Code type</td>
<td>Gold</td>
<td>Pseudo random</td>
<td>N/A</td>
</tr>
<tr>
<td>Carrier</td>
<td>L1</td>
<td>L1, L2</td>
<td>L1, L2</td>
</tr>
<tr>
<td>Feature</td>
<td>Easy to acquire</td>
<td>Precise positioning, jam resistant</td>
<td>Time, ephemeris, HOW</td>
</tr>
</tbody>
</table>

**TABLE 2.1. GPS Signal Structure**

The Coarse/Acquisition (C/A) code is a sequence of zeros and ones and is unique for every satellite. C/A codes are based on Gold Codes. Two sets of gold codes with different phase tapings are used to generate the unique C/A code for every satellite. The C/A code is also called PRN code. These PRN codes are attached to all satellites. If PRN code 9 is incorporated to a satellite, then the it is called as PRN-9 satellite. PRN codes are orthogonal signals, i.e. these signals have the best orthogonal cross-correlation characteristics. The cross-correlation between any two codes is much lower than the auto-correlation of each of the codes. Because of the orthogonal property of PRN codes they are used in all satellite navigation systems. C/A code frequency is 1.023 MHz [33].
The PRN code generator for satellite 1 (PRN-1) is shown in Figure 2.1. As shown, two 10 bit shift registers with different phase tapings are used in PRN code generation. 10 bit length gives a 1023 bit sequence. The clock for the C/A code is 1.023 MHz and for the P-Code is 10.23 MHz. In the GPS navigation system, for all PRN codes phase taping for $G_1$ shift register is done at the delay 10, whereas for $G_2$, depending on phase taping different PRN codes are generated. Here, two phase tapings are taken at delays 2 and 6, to generate the PRN code for the first satellite i.e. PRN01.

Figure 2.2 shows the generation of L1 and L2 signals in the GPS satellite navigation system. The PRN code is modulo 2 added with the navigation data and modulated with the L1 carrier signal. At the same time the P-Code is modulo 2 added with the same navigation data and modulated with the L2 carrier signal. Next the L1 signal is formed by combining both L1 and L2 modulated signals, whereas the L2 signal is formed by only the L2 carrier modulated signal. Section 3.2 describes GPS signal generation in detail.
The P(Y) code is encrypted using an encryption code and is called Y-code. P(Y)-code is a sequence of zeros and ones and is generated using a set of Gold Codes. The frequency of P(Y) code is 10.23 MHz. Navigation data is also a sequence of zeros and ones based at a rate of 50 bits per second. The navigation data and C/A code are modulated with the carrier wave using BPSK (Binary Phase Shift Keying) and DSSS (Direct Sequence Spread Spectrum) techniques. DSSS is a type of CDMA (Code division multiple access), hence all satellites use the same carrier frequency but different code. The GPS signal contains three different bits of information in the navigation data:
A pseudo-random code is the information of the satellite which is sending the signal.

- The ephemeris data contains the date, time and status of satellites (healthy or unhealthy).
- Almanac data contains the information of orbital locations of all satellites including the satellite which is sending the signal.

2.2.2. IRNSS Signal Structure

Based on various considerations, the minimum number of satellites required for the IRNSS constellation is worked out to be 7 (3 GSO and 4 IGSO) [8]. These seven satellites together with the ground based segment provide two kinds of service to users. These services are standard positioning service (SPS), an open service without encryption and restricted service (RS) with encryption. The three satellites at the geosynchronous orbit will be located at 32.5°E, 83°E and 131.5° E respectively. Four inclined geosynchronous orbit satellites will cross the equator at 55° E and 111.75° E (each plane has two satellites) [46].

Depending on the application, users can use three types of receivers to use these IRNSS signals for navigation applications. The three different receivers are single frequency, dual frequency and also a receiver that is compatible to IRNSS and other GNSS signals. The first type, single frequency IRNSS receiver can receive either of the L5 or S band frequencies; the second type is capable of receiving both L5 and S band frequencies. The third type is capable of making use of other GNSS signals in navigation applications. The carrier frequency and bandwidths of L5 and S bands for Standard Position Services are shown in Table 2.2. As shown in the table, L5 and S frequency bands are used in the IRNSS SPS services.

Figure 2.3 shows the modulation scheme performed in IRNSS. As shown, both services are modulated on these carriers: L5 on 1176.45 MHz and S on 2492.028 MHz. The two IRNSS services are standard positioning service and restricted service. The SPS signal is BPSK modulated and mathematically represented by equation (1). Similar to GPS PRN codes, \( C_{SPS} \) is the SPS
TABLE 2.2. Carrier Frequencies and Bandwidths for IRNSS Signal

<table>
<thead>
<tr>
<th>Signal</th>
<th>Carrier Frequency</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS L5</td>
<td>1176.45 MHz</td>
<td>24 MHz (1164.45 - 1188.45 MHz)</td>
</tr>
<tr>
<td>SPS S</td>
<td>2492.028 MHz</td>
<td>16.5 MHz (2483.50 - 2500.00 MHz)</td>
</tr>
</tbody>
</table>

Figure 2.3. IRNSS L5 and S Signal Generation Schematic

ranging code and is chipped at 1.023 Mcps with 1 ms period. $D_{SPS}$ is the data signal which is transmitted by a rate of 50 symbols per second. $C_{SPS}$ and $D_{SPS}$ are modulo two added and then modulated with the L5 carrier signal. In the case of RS, there are two components in quadrature: pilot and data signals. Equations (2) and (3) show mathematical representations of these two signals. Both signals are BOC (5,2) modulated together with their secondary codes (SC). As of now there is not much information about the IRNSS restricted service. This service is only for authorized users of the Indian Government. This is similar to GPS restricted service for L2 band frequency [46]. Symbol definitions for the equations (1), (2) and (3) are shown in Table 2.3.
Table 2.3. Symbol Definitions

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_x(i)$</td>
<td>$i^{th}$ chip of spreading code</td>
</tr>
<tr>
<td>$D_x(i)$</td>
<td>$i^{th}$ bit of navigation message</td>
</tr>
<tr>
<td>$SC_x(t)$</td>
<td>Binary NRZ subcarrier</td>
</tr>
<tr>
<td>$</td>
<td>i</td>
</tr>
<tr>
<td>$[i]_X$</td>
<td>Data bit index for any signal</td>
</tr>
<tr>
<td>$CD_x$</td>
<td>No. of chips per navigation data bit</td>
</tr>
<tr>
<td>$L_X$</td>
<td>Length of spreading code in chips</td>
</tr>
<tr>
<td>$rect_x(t)$</td>
<td>Rectangular pulse function with duration $x$</td>
</tr>
<tr>
<td>$T(c,x)$</td>
<td>Spreading code chip duration</td>
</tr>
</tbody>
</table>

(1) \[ S_{SPS}(t) = \sum_{i=-\infty}^{+\infty} C_{SPS}(i) D_{SPS}(i) rect_{c,sp}(t - iT_{c,sp}) \]

(2) \[ S_{RS,p}(t) = \sum_{i=-\infty}^{+\infty} C_{RS,p}(i) rect_{c,RS,p}(t - iT_{c,RS,p}) SC_{RS,p} \]

(3) \[ S_{RS,d}(t) = \sum_{i=-\infty}^{+\infty} C_{RS,d}(i) D_{RS}(i) rect_{c,RS,d}(t - iT_{c,RS,d}) SC_{RS,d} \]

Figure 2.4 shows the SPS code generation. Similar to the GPS C/A code generation, two 10 bit shift registers are used to generate an SPS code of 1023 bit sequence. The difference in PRN and SPS code generation is that in PRN we do phase tapings for the $G_2$ shift register to generate different PRN codes, whereas in the case of SPS code initial conditions are varied to generate different codes. As shown in figure 2.4, for all SPS codes phase tapping is done for $G_1$ and $G_2$ shift registers at delay 10. Modulo two operation of these two phase tapped signals gives the SPS code.
2.3. Principle and Operation of Satellite Navigation Systems

The basic operational principle of a satellite navigation system is that satellites orbiting above the Earth transmit the time when the signal was sent, satellite ephemeris and other secondary information. GNSS receivers at the ground receive this information to calculate the distance and location of the satellite. Though the principle of receiver working is simple, the operation in real life is a complex process. This section describes the operation of GPS in detail [17].

There are a minimum of 24 active satellites, which send information continuously. As discussed in section 2.2.1, these satellites send three different types of information to the ground. Navigation data contains the orbital data of satellite and current time. Before sending the data to the ground it is modulated with different gold codes (PRN codes) and with dissimilar frequencies to generate L1 and L2 signals.
PRN codes that are added to the navigation data are generated using different phase tapings of the two sets of gold codes. These PRN numbers are different for every satellite. The receiver also has a copy of all PRN codes. When the receiver receives the signal, it tries to correlate the phase of the signal by moving the phase copy back and forth. Once the internally generated and received signal phase patterns match, then the correlator circuit produces a large output to lock the transmitter. By knowing how much this generator has shifted in time, the receiver can find when the signal has arrived. Once the internal clock time with respect to the satellite clock is found, with simple math the pseudo range can be calculated as the distance is equal to multiplication of time with velocity. Using this simple geometry, the receiver can fix its location on a circle with center the satellite position and radius the distance from the satellite. Figure 2.5 shows how the GPS receiver fixes its position on a circle.

![Figure 2.5. Location Tracking with One Satellite](image)

This process is repeated with all the signals that are being received by the receiver. The receiver finds the distance and location of all visible satellites. Then the location of the user can be found easily as shown in figure 2.6.
If the clock at the receiver is accurate, the receiver can calculate its position accurately. But what happens if the clock is not accurate i.e., if it is not exactly synchronized to the transmitter time? GPS cannot calculate the exact location. The error at the receiver clock is called ‘clock offset’. With this error, the GPS receiver cannot decide its location though it locks with three satellites. In figure 2.7, the distances $d_1$, $d_2$ and $d_3$ are from the three satellites to the user. Though the receiver finds the location of the three satellites and the distance between the receiver and satellites, the exact position is not calculated.

To avoid this ambiguity with the location, the receiver adds the clock offset as a unit of time to all the three distances. This unit of time is varied until these circles meet at one location. In figure 2.8, $t$ time units are added to all three distances. In this way, the clock offset can be avoided.
Figure 2.7. Ambiguity in Location Calculation

Figure 2.8. Location of User after Adding \( t \) Time Units
In some cases, if the antenna that receives the signal and the actual GPS receiver are separated by some distance, the time that the signal takes to travel from antenna to the receiver also causes some error in the process of location calculation. Even in this case, some unit of time is added to all the distances till those three circles meet. The GPS receiver antenna plays a crucial role in performance as it needs to receive only required frequencies and there are more advanced antennas available currently [12, 50].

When the receiver receives the signals from three satellites, it can calculate the 2D position and can track the movement of the user. With four or more satellite signals, the receiver can calculate the 3D position (latitude, longitude and altitude). When the user’s location is calculated, the receiver unit can determine other information, such as speed, time to destination, track and sunrise and sunset time and more [26].

2.4. Performance of Satellite Navigation

The performance of a satellite navigation depends on many things. It mainly depends on who owns it, because the performance standards are already set by the owner of the navigation system. For example, the world famous GPS navigation system’s performance is defined by the US government. The document at [http://www.gps.gov](http://www.gps.gov) defines the levels of performance that the US government makes available to users of the GPS Standard Positioning Service (SPS) which is for civil and commercial users. This document can also be found at reference [11]. There is another document in the same website for Precision Positioning Service (PPS), which is also defined by the US government for the levels of performance for authorized users. This document can be found at reference [10]. These documents give the accuracy levels and clear information on the satellite signal structures. The Office of the Secretary of Defense issues these documents on behalf of the US government. Similarly, the performance for all other GNSSs is set by the owners of that GNSS system.

Following are few terms that are used to measure performance of a satellite navigation:
- **Accuracy** refers to the difference between the measured and the real position, speed or time of the receiver.
- **Integrity** refers to a system’s capacity to provide confidence thresholds as well as alarms in the event that anomalies occur in the positioning data.
- **Continuity** refers to a navigation system’s ability to function without interruption.
- **Availability** refers to the percentage of time during which the signal fulfills the accuracy, integrity and continuity criteria.

Apart from these, there are some factors that degrade the performance of the satellite navigation and create location inaccuracies. Some of them are delays in the ionosphere and troposphere or atmospheric effects, signal multi-path, clock errors in the receiver, signal jammers, etc. [44, 36].
CHAPTER 3
MULTI GLOBAL NAVIGATION SATELLITE SYSTEM DESIGN IN SIMULINK®

3.1. Multi GNSS Navigation System

With Multi GNSS Navigation systems, the receiver can make use of two or more GNSS signals in location determination. In this thesis, two such navigation systems, namely the GPS and the IRNSS are designed and examined. The high-level design of a Multi GNSS navigation system in Simulink® is shown in figure 3.1. As shown, there are two transmitters to generate GPS and IRNSS signals, two channels to create noise environments and two branches in the receiver to acquire the GPS and IRNSS satellite signals. The display and scope are connected to calculate the error rate and to observe the transmitted and received signals.

The algorithm for the operation of the GNSS navigation system in Simulink® is shown in figure 3.2. As shown, first, one of the satellites is to be selected among the available 24 GPS satellites and another from the 7 IRNSS satellites. At the same time, navigation data are generated. These signals are modulo 2 added. This signal is then given as input to the BPSK modulation block. After modulation, signal is sent through the channel.

**Figure 3.1. Multi GNSS Navigation System Design**
In the channel, the signal is added with certain selected noise models and sent to the receiver module. Here, the signal is demodulated using BPSK demodulator and then using the parallel search algorithm, maximum correlated PRN signal is determined. Next, the EXOR operation is performed between the received signal and the maximum correlated PRN code to extract the navigation data from the received signal.

3.2. GPS Transmitter

L1 signal generation at the GPS transmitter and details of navigation data are discussed in this section. In the GPS system Coarse/Acquisition (C/A) and precise codes are used to encode the navigation data. To extract the navigation data from the received signal, the receiver must know either of the codes. Precise code is used to provide greater accuracy in military applications whereas C/A codes are used for civilian applications. C/A codes are also called Pseudo Random Noise (PRN) signals. The Positioning service provided by this code is called Standard Positioning Service (SPS).

The GPS transmitter is shown in figure 3.3 [37]. The very first block in the multi GNSS model chooses the satellite number from 24 available transmitters. This value is given as input to the PRN Code Generator for GPS module. The internal circuit of this module is shown figure 3.5. Based on the value given, a multi-port switch transmits one of the 24 generated PRN codes to the Tx EXOR block. Another input for this block is the navigation data generated from the Bernoulli Binary Generator. For simplicity, the navigation data are assumed to be random binary data. The data type of the EXOR output is Boolean in the Simulink® environment. To perform BPSK modulation, the data type is converted to Double using Data Type Conversion block. BPSK modulation changes the bit stream containing 0s and 1s to a bit stream of +1s and -1s. BPSK modulation helps to reduce the Bit Error Rate (BER) during transmission. The signal is multiplied with a signal frequency of 1575.42 MHz (L1 band) and this signal is transmitted to the channel block.
PRN codes (1-24 for GPS & 1-7 for IRNSS) At Receiver

Choose satellite (1 – 24 & 1-7)

PRN codes (1-24 for GPS & 1-7 for IRNSS) At Receiver

Correlate received Signal with all Local PRN codes

Choose PRN that correlated maximum

EXOR

Extract Navigation Data

End

Figure 3.2. Algorithm for Multi GNSS in Simulink®
3.2.1. PRN Code Generator

C/A codes are generated using two sets of gold codes. As shown in the equations below, polynomial \( G_1 \) and polynomial \( G_2 \) are fixed for all PRN code generators. With different phase tapings in polynomial \( G_2 \) different PRN codes are generated [27]. The phase tapings for all 24 satellites are shown in Table 3.1.

The two polynomials used in GPS gold codes are,

\[
G_1(x) = 1 + x^3 + x^{10} \tag{4}
\]

\[
G_2(x) = 1 + x^2 + x^3 + x^6 + x^8 + x^9 + x^{10} \tag{5}
\]

In Simulink\textsuperscript{®} the polynomials can be modeled with the help of delay blocks. The single delay block is shown in 3.4. These delay blocks in Simulink\textsuperscript{®} are used to delay the input signal for one sample period. With the help of 20 such delay blocks, these two polynomials can be implemented. Figure 3.5 shows all the PRN code generators of the 24 satellites, which are connected to a multi-port switch. Once the PRN code Generator is expanded, each module from PNR01 to PNR24 is used to generate the PRN code from satellite 01 to satellite 24, respectively.
<table>
<thead>
<tr>
<th>SV PRN ID</th>
<th>G2 Phase Taps</th>
<th>First 10 Chips</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2&amp;6</td>
<td>1100100000</td>
</tr>
<tr>
<td>2</td>
<td>3&amp;7</td>
<td>1110010000</td>
</tr>
<tr>
<td>3</td>
<td>4&amp;8</td>
<td>1111001000</td>
</tr>
<tr>
<td>4</td>
<td>5&amp;9</td>
<td>1111100100</td>
</tr>
<tr>
<td>5</td>
<td>2&amp;9</td>
<td>1001011011</td>
</tr>
<tr>
<td>6</td>
<td>2&amp;10</td>
<td>1100101101</td>
</tr>
<tr>
<td>7</td>
<td>1&amp;8</td>
<td>1001011001</td>
</tr>
<tr>
<td>8</td>
<td>2&amp;9</td>
<td>1100101100</td>
</tr>
<tr>
<td>9</td>
<td>3&amp;10</td>
<td>1110010110</td>
</tr>
<tr>
<td>10</td>
<td>2&amp;3</td>
<td>1101000100</td>
</tr>
<tr>
<td>11</td>
<td>3&amp;4</td>
<td>1110100010</td>
</tr>
<tr>
<td>12</td>
<td>5&amp;6</td>
<td>1111101000</td>
</tr>
<tr>
<td>13</td>
<td>6&amp;7</td>
<td>1111110100</td>
</tr>
<tr>
<td>14</td>
<td>7&amp;8</td>
<td>1111111010</td>
</tr>
<tr>
<td>15</td>
<td>8&amp;9</td>
<td>1111111101</td>
</tr>
<tr>
<td>16</td>
<td>9&amp;10</td>
<td>1111111110</td>
</tr>
<tr>
<td>17</td>
<td>1&amp;4</td>
<td>1001101110</td>
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<tr>
<td>18</td>
<td>2&amp;5</td>
<td>1100110111</td>
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<tr>
<td>19</td>
<td>3&amp;6</td>
<td>1110011011</td>
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<td>1111001101</td>
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<tr>
<td>21</td>
<td>5&amp;8</td>
<td>1111100110</td>
</tr>
<tr>
<td>22</td>
<td>6&amp;9</td>
<td>1111110011</td>
</tr>
<tr>
<td>23</td>
<td>1&amp;3</td>
<td>1000110011</td>
</tr>
<tr>
<td>24</td>
<td>4&amp;6</td>
<td>1111000110</td>
</tr>
</tbody>
</table>

Table 3.1. GPS C/A Code Assignments
For example, figure 3.6 shows the PRN code generator for satellite 1 and the phase taping is at delays 2 and 6, whereas figure 3.7 shows the PRN code generator for satellite 2 and the phase taping is at delays 3 and 7.

As shown in figure 3.6, 20 different delay blocks are used to model the two polynomials. Initial condition for all delay blocks is ‘1’. As shown, for the $G_1$ polynomial the phase tapings are taken at delays 3 and 10 and given as feedback to the same polynomial, whereas, for $G_2$ the polynomial phase tapings are taken at delays 2, 3, 6, 8, 9 and 10 and given as feedback to the same polynomial. To obtain the PRN-1 code from these two polynomials, two inputs, one from delay 10 of $G_1$ and the other from the EXOR of phase tapings at delays 2 and 6 of $G_2(t)$ are modulo 2 added. The same design is done for 23 other PRN code generators, except for the fact that phase tapings for the $G_2$ polynomial are different, as shown in Table 3.1.

Another code present in GPS is the Precise code, which is also known as the P(Y) code. This encryption is used for military applications. This code is only known to people who are authorized by the US Government. The Positioning service provided by this code is called the Precise Positioning Service (PPS). Without knowing the Precise code structure, generation and observation is not possible. For this reason, this thesis is concentrated only on C/A encrypted L1 signals [19].
Figure 3.5. PRN Code Generator for GPS
FIGURE 3.6. PRN Code Generator for GPS Satellite 1

FIGURE 3.7. PRN Code Generator for GPS Satellite 2
3.2.2. Navigation Data Generation

As discussed in section 2.2.1, the GPS transmitter’s navigation data consist of Ephemeris and Almanac Data, which helps the receiver find its location. Navigation data in real life are highly sophisticated and provide complete information about date, time, health and location of each satellite. In this thesis, navigation data are assumed to be random binary data as the objective is to acquire the satellite signal. At the receiver, the transmitted and received navigation data are compared to find accuracy. The Bernoulli Binary Generator block is used to generate random binary data using a Bernoulli distribution. This block also has a feature to specify the probability of zeros and ones in the generated random data.

3.2.3. BPSK Modulation and Transmission

The EXOR operation is performed on the generated navigation data with one of the C/A codes. The selection of C/A code out of the 24 available is done by providing a constant number from 1 to 24 before the beginning of the simulation. Table 3.2, gives the truth table for the logical operation of EXOR. After this, the signal is transmitted to the BPSK modulator where a sequence of zeros and ones is changed to a sequence of ones and negative ones. Then, the signal is multiplied with L1 frequency, i.e. 1575.42 MHz, and is transmitted to the channel block. In BPSK modulation the phase of the carrier signal is varied according to the input data. The amplitude and frequency remain unchanged [47]. BPSK takes data inputs one bit after the other and varies the phase of the carrier depending on the input bit.

\[
\begin{array}{c|c|c}
A & B & A \oplus B \\
0 & 0 & 0 \\
0 & 1 & 1 \\
1 & 0 & 1 \\
1 & 1 & 0 \\
\end{array}
\]

**TABLE 3.2. EX-OR Truth Table**
The constellation diagram for BPSK modulation is shown in figure 3.8. As shown, for input ‘0’ the carrier phase doesn’t change, whereas for input ‘1’ the carrier phase changes to 180°.

The advantage with BPSK modulation is that it is more robust to noise as it has to take the highest level of noise to make an incorrect decision at the receiver. But the disadvantage with BPSK is that it encodes only one bit at a time. It cannot be used in high speed data transmission applications. The following expression is the mathematical representation of BPSK modulation.

\[
S_n(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t + \pi(1 - n)) \quad n = 0, 1
\]

where \(E_b\) is the energy per bit, \(T_b\) is the bit duration and \(f_c\) is the carrier frequency.
3.3. IRNSS Transmitter

The IRNSS transmitter is present in the space segment in real life. Figure 3.9 shows the IRNSS transmitter design in Simulink®. Similar to GPS, one of the available 1 to 7 PRN codes is selected using a constant block. Depending upon the number given, the respective satellite PRN code is selected by the multi-port switch and is given to the EX-OR gate. The other input for this gate is the navigation data generated by the Bernoulli Binary block. The two input signals are modulo 2 added. The modulo 2 added signal is in boolean format and to perform BPSK modulation, this signal needs to be converted to type ‘double’. After converting the signal to data type ‘double’, it is fed to the BPSK modulator. After modulating the input signal, the output is multiplied by the carrier signal with the frequency of L5 band, i.e. 1176.45 MHz, generated by the sine wave block. The multiplication is done using a block called ‘Product’. Next the signal is transmitted through the AWGN channel. The sub-sections in this section describe all modules in the IRNSS transmitter in detail.

3.3.1. PRN Code Generator

Similar to GPS, PRN codes for IRNSS are generated using two polynomials. Polynomial $G_1$ and polynomial $G_2$ are fixed for all PRN code generators. With different initial conditions in the $G_2$ polynomial, different PRN codes are generated as shown in figure 3.10.
The two polynomials used in IRNSS are

\begin{equation}
G_1(t) = 1 + x^3 + x^{10}
\end{equation}

\begin{equation}
G_2(t) = 1 + x^2 + x^3 + x^6 + x^8 + x^9 + x^{10}
\end{equation}

Initial conditions for the G2 register and first 10 chips (in octal format) for both L5-SPS and S-SPS are shown in tables 3.3 and 3.4 respectively. The octal representation for the first 10 chips is done in a specific way. In the four digits of the octal representation, the first digit indicates the first chip among the 10 chips. The remaining 9 chips are represented in 3 octal bits [18]. In this thesis only the L5-SPS signal is considered.

<table>
<thead>
<tr>
<th>PRN ID</th>
<th>Initial condition for G2 Register</th>
<th>First 10 Chips in Octal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1110100111</td>
<td>130</td>
</tr>
<tr>
<td>2</td>
<td>0000100110</td>
<td>1731</td>
</tr>
<tr>
<td>3</td>
<td>1000111010</td>
<td>0713</td>
</tr>
<tr>
<td>4</td>
<td>0101110010</td>
<td>1215</td>
</tr>
<tr>
<td>5</td>
<td>1110111000</td>
<td>0117</td>
</tr>
<tr>
<td>6</td>
<td>0001110111</td>
<td>1624</td>
</tr>
<tr>
<td>7</td>
<td>0000010100</td>
<td>1753</td>
</tr>
</tbody>
</table>

**TABLE 3.3. Code Phase Assignment for IRNSS L5-SPS Signals**

These polynomials are modeled using delay blocks in Simulink®. As shown in the tables, the initial conditions are set for the \( G_2 \) polynomial. These 7 PRN codes are connected to the Multi Port Switch as shown in figure 3.10. Using the constant block one of these 7 PRN codes can be selected and sent to the further blocks in the transmitter. The internal circuit of ‘IRNSS PRN code generator’ is shown in figure 3.11.
<table>
<thead>
<tr>
<th>PRN ID</th>
<th>Initial condition for G2 Register</th>
<th>First 10 Chips in Octal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0011101111</td>
<td>1420</td>
</tr>
<tr>
<td>2</td>
<td>0101111101</td>
<td>1202</td>
</tr>
<tr>
<td>3</td>
<td>1000110001</td>
<td>0716</td>
</tr>
<tr>
<td>4</td>
<td>0010101011</td>
<td>1524</td>
</tr>
<tr>
<td>5</td>
<td>1010010001</td>
<td>0556</td>
</tr>
<tr>
<td>6</td>
<td>0100101100</td>
<td>1323</td>
</tr>
<tr>
<td>7</td>
<td>0010001110</td>
<td>1561</td>
</tr>
</tbody>
</table>

TABLE 3.4. Code Phase Assignment for IRNSS S-SPS Signals

3.3.2. Navigation Data Generation

As discussed in section 3.2.2, navigation data for this thesis are considered as random data generated from the ‘Bernoulli Binary generator’ block. In real life, The IRNSS navigation data master frame comprises of four sub-frames. Each sub-frame is 600 symbols, transmitted at 50 samples per second. Each sub-frame has a 16 bit Sync word followed by 584 bits of interleaved data. The information in navigation data is almost the same as in GPS. The information is mainly divided into two parts: primary navigation parameters and secondary navigation parameters. Along with these two parameter sets, an idle pattern, containing alternating zeros and ones is transmitted in the data of the navigation sub-frames.

3.3.3. BPSK Modulation and Transmission

In IRNSS, the Standard Position Service (SPS) signal is modulated on both L5 and S bands using BPSK modulation. Navigation data with a bit rate of 50 bps are modulo 2 added to the PRN code. This CDMA modulated code, modulates L5 and S carriers at 1176.45MHz and 2492.028 MHz, respectively. The BPSK modulated signal is sent to the channel block to be transmitted to the receiver. BPSK modulation uses two phase changes for carrier signal based on whether the input data is 0 or 1.
Figure 3.10. PRN Code Generation for Seven IRNSS Satellites

This modulation is more robust as it has less probability of error. This is because the distance between the symbol points in the constellation is larger than any other PSK modulation. Equations for BPSK modulation are given in Section 3.2.3.

3.4. Channel

The channel plays an important role in any satellite navigation system because accuracy of location determination highly depends on channel noise. In real life, the channel is free space for any navigation system. It is important to analyze the performance of any system characteristics under different wireless channel parameters and device structures. The performance is evaluated by observing the Bit Error rate (BER) at the receiver. Loss of signal in channel is commonly
FIGURE 3.11. PRN Generator for IRNSS Satellite 1

called as fading and is a very important phenomenon in wireless channels [13]. Even though no model perfectly describes the environment, the better the model describes a fading environment, the better the design can be. To get accuracy of position, all this degradation on signals should be considered while designing the receiver. In this thesis, three different channel noise distributions namely AWGN, Rayleigh and Rician models are used [14]. This section introduces these three channel distributions.

3.4.1. AWGN Channel

The AWGN noise channel is considered as the simplest radio environment in which a wireless communication system can operate. This distribution is a basic communication channel model and is commonly used. The signal is transmitted in the channel and simulated background noise is added to the signal. In a simple AWGN channel, the transmitted signal is added to the noise in the channel and this signal is received at the receiver [14]. This channel can be modeled using a single block in Simulink®. The AWGN Channel (Additive-White Gaussian Noise) block is shown in figure 3.12. This block creates noise in the channel. A Gaussian noise channel environment with tunable noise variance is created.
The mathematical expression for the received signal in the AWGN channel model is:

\[ r(t) = s(t) + n(t) \] (9)

In the above expression, \( s(t) \) is the transmitted signal and \( n(t) \) is the background noise.

The mathematical expression for the noise variance is:

\[ \text{NoiseVariance} = \frac{\text{SignalPower} \times \text{SymbolPeriod}}{\text{SampleTime} \times 10^{\frac{E_s}{N_0 \times 10}}} \] (10)

In the above expression, \( E_s \) is signal energy (Joules) and \( N_0 \) is the noise power spectral density (Watts/Hz).

This channel does not account for fading, interference or non-linearity. Simple linear addition of wideband or white noise with a constant spectral density to the transmitted signal is done. The assumptions when using this model are that the noise is additive and white with Gaussian distribution [45].
3.4.2. Multipath Rayleigh Fading Channel

This channel can be modeled using a single block in Simulink®. The Rayleigh Channel block is shown in figure 3.13. It occurs when there is no direct path between the transmitter and receiver. The resultant signal is the sum of the all reflected, diffracted and scattered signals. This is primarily due to the multi-path reception.

![Multipath Rayleigh Fading Channel Block](image)

**Figure 3.13.** Multipath Rayleigh Fading Channel Block in Simulink®.

The Rayleigh model is a statistical time varying model for the effects in troposphere and ionosphere propagations. It is also a statistical model for urban areas, where objects attenuate, reflect, refract and diffract the signal. It is well known that the envelope of the sum of two quadrature Gaussian noise signals obeys a Rayleigh distribution [49]. In this model as the signal strength weakens, it is difficult to detect the primary component in the received signal. This model best describes the propagation medium where the signal travels in different paths to reach the receiver.

The effect of Rayleigh fading is that it embraces constructive and destructive interference, and phase shifting of the signal. Depending on the signal phase and gain mutli-path signals create various noise levels in the signal received at receiver.
The received signal can be mathematically represented as:

\[ R(n) = h(n, \tau)S(n - m) + w(n), \]  

(11)

where \( w(n) \) is AWGN noise with zero mean and unit variance and \( h(n) \) is the channel impulse response [45] which is represented as:

\[ h(n) = \alpha(n)e^{-j\theta(n)}, \]  

(12)

where \( \theta(n) \) is the phase shift and \( \alpha(n) \) is the attenuation for \( n^{th} \) path. Depending on the bandwidth of signal and channel, this fading is of two types. If the coherence bandwidth of the channel is larger than the signal bandwidth, the channel is a flat fading channel, otherwise it is a frequency-selective fading channel.

### 3.4.3. Multipath Rician Fading Channel

This channel can be modeled using a single block in Simulink®. The Rician Channel block is shown in Figure 3.14. It occurs when there is a strong direct path between the transmitter and receiver as well as other multi-path signals. This strong component is a non fading signal and is commonly termed as Line of Sight (LOS) component. Figure 3.15 shows a model of the Rician fading channel. As shown, there are three paths between the transmitter and receiver, one is a direct path and two are reflected paths [3].

In this model, the received signal comprises of both a LOS component and scattered multi-path waves. The amplitude gain is characterized by a Rician distribution. The Rician distribution is characterized by the Rice factor \( k \), which shows the relative strength of the LOS path signal over the multi-path signal [45]. The mathematical expression of the Rice factor \( k \) is:

\[ k = \frac{m}{2\sigma^2}, \]  

(13)

where \( m \) is the power of the dominant component and \( \sigma^2 \) is the local-mean scattered power.
Rician fading occurs when one of the paths, typically a line of sight signal, is much stronger than the others. In the simulations the $k$ factor is varied to observe the effect of Bit Error Rate at the receiver, whereas in Rayleigh modeling by varying the gain and delays of different paths, the BER is analyzed.

After modeling of the channel for both GPS and IRNSS systems, these signals are given to a manual switch. Depending on which transmitter the switch is connected to, the respective branch can be examined for power calculation and accuracy. This multi-port switch in Simulink® helps
the receiver to receive either of the GPS or IRNSS transmitted signals. In real life, this receiver can be designed in a way such that it can receive both signals and process accordingly to extract the navigation data and find the location eventually.

3.5. GPS Receiver

This section describes the GPS receiver and its sub-components. Figure 3.16, shows the designed GPS receiver in Simulink®. When the signal is received by the GPS receiver from the channel, it first filters out other frequency signals using a Band Pass Filter (BPF). The output of BPF is multiplied with the same carrier that is used at the transmitter. After that, the signal is multiplied with the local PRN sequence, which is the same as that used at the transmitter. To generate the same carrier and code, Phase Locked Loop (PLL) and Delay Locked Loop (DLL) circuits are used. Figure 3.17 shows a simple design, where the incoming signal is multiplied with the local carrier generator and the local PRN code sequence.

![Diagram of GPS Receiver](image)

**Figure 3.16. GPS Receiver**

This thesis is concentrated on acquiring the satellite. The acquisition module present at the front of the receiver is used to acquire the visible satellite. The received signal is correlated with all local PRN signals to check for the maximum correlated PRN sequence. After determining it, the receiver multiplies the received signal with the maximum correlated signal.

After code and carrier tracking, the navigation data are extracted from the received signal. It contains information about satellite position, time and status of the satellite. After extracting the
data from the received signal, the pseudo range (distance) from the satellite is calculated by the receiver. At this time the receiver knows that the location is in the form of a surface of a sphere with the satellite at its center and radius the pseudo range.

To calculate the exact location of the user, the receiver should receive the signal from at least three or more satellites. When the number of visible satellites is more than three, the receiver calculates the pseudo range for all visible satellites to locate its position on different spheres centered around visible satellites and radii as respective pseudo ranges. The intersection of all spheres gives the location of user. For a cold start this process for a normal GPS receiver takes approximately 10 to 12 minutes.

Because of the degradation in signal and errors in distance calculation, the pseudo range calculated may not be accurate. Therefore, instead of one point, the intersection produces a small region to find the location. This can be overcome by adjusting the pseudo ranges for multiple satellite distances, thus reducing the area of intersection. Another way is to have more visible satellites to find the exact location.
3.5.1. Band Pass Filter

The first block in the GPS receiver is the Band Pass Filter (BPF). It is designed using the fdatool in Matlab®. This tool is a special filter designing analytical tool in Matlab® signal processing toolbox [24]. Using this tool, almost every traditional filter can be designed. The required center frequency for BPF is 1575.42 MHz with 0.2 GHz of bandwidth.

The frequency response is characterized by the magnitude of the system’s response, typically measured in decibels (dB). The magnitude response of the BPF consists of both Low pass filter and High pass filter’s magnitude response. It is mathematically expressed as:

$$|G(jw)| = \frac{|K\tau_2w|}{\sqrt{1 + \tau_1w^2_1}\sqrt{1 + \tau_2w^2_2}}$$

where $K$ is the sensitivity or gain of the system, $\tau_1$ is the system time constant for LPF, $\tau_2$ is the system time constant for BPF and $w_c$ is the cut-off frequency. The Magnitude response for the BPF used in GPS receiver is shown in figure 3.18. It clearly shows that only signal frequencies between 1.4 GHz to 1.6 GHz are allowed with minimum attenuation. All other signals are highly attenuated. For multi-channel navigation receivers, reconfigurable RF sampling is needed to determine the required gain, noise figure, ADC dynamic range and sampling frequency based on GNSS standards specifications [15].

3.5.2. BPSK Demodulation

The band passed signal is given to one of the inputs of a multiplier, while the other input is provided by the sine wave generator. The sine wave generates the same carrier signal that was used at the GPS transmitter. After multiplication, the signal is fed to the BPSK demodulation block to demodulate the received signal. The signal is modulo 2 added with the same PRN code used at the transmitter, which gives the navigation data. To find the exact PRN signal used at the receiver this demodulated signal is fed to the acquisition module.
3.5.3. Acquisition

To track a GPS signal, first the receiver should acquire the satellite by finding its number. Figure 3.19 shows how acquisition is done in three simple steps. In the first step the received signal is correlated with all local copies of PRN signals. In the second step, receiver finds which PRN is maximum correlated with the received signal. In the final step, the received signal and maximum correlated signals are modulo 2 added [43].

This can be easily done by finding the maximum value of all correlation values. As PRN signals are orthogonal signals, the received signal gives very high correlation value when it is correlated with the PRN code used at the transmitter. The algorithm is implemented in Simulink® as shown in figure 3.20. As shown, the same 24 PRN codes used at the transmitter are used in the acquisition module. The received signal from the BPSK demodulation block is correlated with all 24 PRN codes.
Correlate received signal with all local generated PRN codes

Compare and find which local PRN code highly correlated

EXOR received signal with highly correlated PRN code

Navigation Data

**FIGURE 3.19.** Acquisition Algorithm
Figure 3.20. Acquisition Module in Simulink®
The mathematical expression for the correlation is:

\[ r_{xy}(l) = \sum_{-\infty}^{\infty} x(n) \times y(n-l); \quad l = 0, \pm 1, \pm 2, \ldots \]  

(15)

\[ r_{xy}(l) = \sum_{-\infty}^{\infty} x(n-l) \times y(n); \quad l = 0, \pm 1, \pm 2, \ldots \]  

(16)

All these 24 correlation values are given as inputs to the 24×1 multiplexer. The output of this block is given to the maximum block. This block computes the maximum value along the specified dimension of the input or across time (running maximum). The index for which maximum correlation value is present is given as the output from this block, which is given as input to the PRN code generator module. In real life, receivers store these PRN codes in memory instead of generating them each and every time.

3.5.4. Navigation Data Extraction

Navigation data extraction is easily done when the satellite number is being acquired by the acquisition module. The received signal is modulo 2 added with the highly correlated PRN signal which gives the navigation data. Because of the noisy channel, wide band pass filter and some other effects the extracted navigation data may not be exactly the same as those sent by the receiver.

There is another module called tracking in receivers, which is not covered in this thesis. This module basically tracks the satellite when it is acquired by the acquisition module. Unless the satellite is invisible to the user, the GPS receiver continuously listens to the satellite to determine location, speed and direction.
3.6. IRNSS Receiver

The IRNSS receiver design is similar to the GPS receiver. Figure 3.21 shows the implementation of the IRNSS receiver in Simulink®. The received signal is first fed to the BPF to attenuate all frequencies except the required L5 frequency. This band passed signal is given to the product block to be multiplied with the local generated carrier signal. After multiplying, the output is given to BPSK demodulator. Next, BPSK demodulation for the received signal is performed, i.e. data streams of negative ones and positive ones are transformed to zeros and ones. This data stream is given to an acquisition module to acquire the satellite number. After determining the number, the respective PRN code is generated from the local PRN generation module. The received signal and locally generated PRN codes are modulo 2 added to extract the navigation data. The following sub-sections give detailed explanation of all modules present in the IRNSS receiver.

![Figure 3.21. IRNSS Receiver](image)

3.6.1. Band Pass Filter

The first block in the IRNSS receiver is the Band Pass Filter (BPF). The BPF is an electronic device that allows certain range of frequencies and discards all other frequencies.
The two types of BPFs are active filter and passive filter. If the BPF requires external power source because of active components present in it, it is called an active BPF. If the BPF contains only passive components and does not require any external power source, then it is called a passive BPF. For IRNSS also it is designed using the fdatool in MATLAB®. The required center frequency for the IRNSS BPF is 1176.45 MHz with 0.2 GHz of bandwidth. This filter allows frequencies between 1 GHz to 1.2 GHz and attenuates all other frequencies. In this way all other frequencies can be filtered out at the front end of the receiver. The magnitude response for the BPF used in the IRNSS receiver is shown in Figure 3.22. As shown in the figure, the band pass filter allows frequencies that range from 1 GHz to 1.2 GHz and attenuates all other frequencies. In this project only two navigation systems are considered; to make use of more GNSS signals the BPF response should be narrowed to attenuate other navigation systems signals.

**Figure 3.22.** IRNSS BPF Filter Magnitude Response
3.6.2. BPSK Demodulation

BPSK demodulation is the next block after the received signal is filtered using BPF. The signal generated by the Sine Wave Generator is multiplied with the received signal using a Product block. Using the BPSK Demodulator block, the data stream is reconverted to the zeros and ones. Details of BPSK modulation have been previously discussed in Section 3.2.3.

3.6.3. Acquisition

Acquisition is the major module in any GNSS receiver. Only after acquisition, the satellite is tracked and the location is determined. Figure 3.23, shows the Acquisition module of the IRNSS receiver.

![Figure 3.23. IRNSS Acquisition Module](image)
The received signal and locally generated PRN codes are given as inputs to the correlation blocks. Output samples of each correlation block are integrated to find the maximum correlated signal. The maximum correlated PRN code’s index is transmitted to further blocks of the IRNSS receiver module. In the correlation block, correlation between the received signal and locally generated IRNSS PRN codes is performed. As these PRN signals are orthogonal, the correlation is maximum for the PRN code that is used at the transmitter. The correlated samples are added using the integrator method, i.e. each sample is delayed and added to the next sample. This is done for all samples which produces correlation as a number. The same is repeated for all seven PRN codes and given to the 7×1 multiplexer. The output from the multiplexer is given to a maximum block, which outputs the index of PRN that is maximum correlated with the received signal. In this way the acquisition is done at the receiver end.

3.6.4. Navigation Data Extraction

After successful completion of acquisition, the determined satellite number is given to the input of the locally generated PRN codes. Depending on the satellite number acquired, the respective PRN code is chosen from the seven generated IRNSS PRN codes. The received signal and locally generated PRN copy are modulo 2 added to extract the navigation data. For analysis purposes, this received navigation data is compared with the transmitted one.
CHAPTER 4

OBSERVATIONS AND ANALYSIS

4.1. Scope Outputs

In Simulink®, one can observe the signal at any point using the Scope block. After the successful design of the multi GNSS receiver, its performance is observed based on several simulations. The main components in this design are the PRN code generator at the transmitter, BPSK modulation and demodulation, navigation data generation and extraction and also correlation at acquisition. In this section different operations performed on the signal are elaborated using the scope block display.

4.1.1. GPS and IRNSS PRN Codes

Pseudo Random Noise (PRN) codes for both GPS and IRNSS are generated using two sets of gold codes. In GPS, different phase tapings for the second \((G_2)\) polynomial give 24 PRN codes, whereas different initial conditions for the same second polynomial give 7 PRN codes for IRNSS. PRN codes are orthogonal, i.e. they give high correlation when correlated with the code itself than with any other PRN code. In both navigation systems we are using PRN codes with 1023 chips. These repeat after every 1023 chips. For every millisecond, one set of 1023 PRN codes are generated. The same copy of PRN codes are present at the receiver to perform the correlation with the received signal. Figure 4.1 shows the first 50 samples. These are out of 1023 samples in PRN01 for both GPS and IRNSS. In IRNSS, the first 10 chips are inverse of the initial conditions of second polynomial. After that, the feedback path affects the output.

4.1.2. BPSK Modulation and Demodulation

In satellite navigation systems, phase shift keying techniques are used in modulation schemes. In both GPS and IRNSS, BPSK modulation is used. The advantage of BPSK is its low Bit Error Rate in comparison to other phase shift keying techniques.
Figure 4.1. First Fifty Chips of PRN 1 for GPS and IRNSS

Figure 4.2, shows three plots. The first plot is modulo 2 added navigation data and PRN code. The second plot shows the same signal after BPSK modulation. The last one shows the signal after BPSK demodulation. Before the modulation, the data is a sequence of zeros and ones. During modulation, the input data bits are converted to a sequence of ones and negative ones. After the demodulation the data is recovered and represented in zeros and ones again. BPSK modulation is a simple digital modulation scheme, which encodes the input signal using phase variation of the carrier with 180°.
4.1.3. Navigation Data

Comparison of the transmitted and received navigation signals is shown in figure 4.3. These are plotted under ideal conditions, i.e. without any variation in phase and frequency (noise variance is set to zero, without any Doppler or multi path effects). Even though this plot shows no errors between the transmitted and received navigation signals, when observed after increasing the noise levels there are some errors. In real life, the extracted navigation data is not exactly the same as the transmitted one. Even with few errors, the receiver can determine its location.
As discussed earlier, this research is concentrated on design of multi GNSS receiver to acquire satellites. For this reason the navigation data is generated by a Bernoulli Binary Generator.

4.1.4. Correlation

Correlation is a mathematical process that compares two input signals and gives an output sequence which describes the correlation of the inputs. If the same two signals are correlated, it is called the Auto-Correlation Function (ACF).

Figure 4.3. Transmitted and Received Navigation Data Comparison
In GNSS receivers, correlation is the key operation to synchronize with the incoming signal and to retrieve the navigation message. In any navigation system, we use Pseudo-Random Noise (PRN) Codes, which are orthogonal. Correlation of any PRN code with itself is very high compared to correlation with any other PRN code. This orthogonal property of PRN codes helps to recover the message from the received signal using the correlation operation.

In Simulink® the Correlation block helps to perform this operation. In the Acquisition module, the received signal is correlated with all local PRN codes using this block. The mathematical expressions for correlation are given in equations (17) and (18):

\[
(17) \quad r_{xy}(l) = \sum_{-\infty}^{\infty} x(n) \times y(n-l); \quad l = 0, \pm 1, \pm 2,.. \\
\]

\[
(18) \quad r_{xy}(l) = \sum_{-\infty}^{\infty} x(n-l) \times y(n); \quad l = 0, \pm 1, \pm 2,.. \\
\]

When the PRN1 code is used at the transmitter as a ranging code, correlation with PRN1 should be maximum at the receiver. In the receiver, after demodulation of the received signal, the Acquisition module tries to find out which satellite signal is received. For this it correlates the demodulated signal with all local copies of PRN codes. After the correlation, the maximum correlated PRN code is used to extract the navigation data. Figures 4.4 and 4.5 show the correlation of different local PRN sequences with the received signal. Figure 4.4 shows the maximum correlation when PRN1 is correlated with received signal. Figure 4.5 shows minimum correlation when PRN2 is correlated with the received signal. This is because PRN1 is used at the transmitter. Using these correlated values acquisition of satellite is performed in GPS receivers.
Figure 4.4. Maximum Correlation between PRN1 Code and Received Signal

Figure 4.5. Minimum Correlation between PRN2 Code and Received Signal
4.2. Signal Observations

To test the receiver, three channel models are considered: AWGN model, Rayleigh and Rician fading channel models. For all models, the relation between Signal to Noise Ratio (SNR) and Bit Error Rate (BER) is compared. Along with this comparison, some other observations depending on the channel model are also performed. In this section analysis of three noise models and BER are discussed.

4.2.1. AWGN Channel

The AWGN channel is the simplest and most commonly used noise model in many applications. White Gaussian noise is linearly added to the transmitted wideband signal. To test the designed receiver performance, the AWGN channel model is considered to observe the power received and the bit error rate of the receiver. Three observations are made using this model. They are: power received vs. noise variance of the channel, BER vs. noise variance and finally BER vs. signal to noise ratio. This subsection presents the analysis of these observations.

4.2.1.1. Power Received (dBm) vs. Noise Variance for AWGN Channel

For this first observation, the noise variance of the AWGN channel is gradually varied while noting down the power of the received signal at the receiver. The power is calculated at the front-end of the receiver and the variance of noise is varied using the control panel of the AWGN Channel block.

Figure 4.6. Signal Power Calculation
<table>
<thead>
<tr>
<th>Si.No.</th>
<th>Noise Variance</th>
<th>Power received (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>26.99</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>29.94</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>31.84</td>
</tr>
<tr>
<td>4</td>
<td>1.5</td>
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</tr>
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<td>2</td>
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<td>6</td>
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<td>34.59</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>35.55</td>
</tr>
<tr>
<td>8</td>
<td>3.5</td>
<td>36.01</td>
</tr>
</tbody>
</table>

TABLE 4.1. Power Received (dBm) vs. Noise Variance for AWGN Channel

The power of the received signal is calculated using the dB Conversion block. When converting the power of the received signal to dBm, the reference power is 1 mWatt. To use this block, some other modules are needed to be connected before this. As shown in figure 4.6, the received signal is given to the buffer which stores samples of the signal depending on the buffer length. Then the Variance block tracks the variance of the sequence of inputs over a period of time and this is given as input to the dB conversion block. Subsequently it is converted to dBm displayed to the user using a Display block. The following expressions give the mathematical models for dBm calculation of power and voltage inputs, respectively:

\[
y = 10\log_{10}(u) + 30
\]  

\[
y = 10\log_{10}(|u|^2) + 30
\]

In equation (19), \( u \) is a real, nonnegative, power signal (units of watts). In equation (19), \( u \) is a real voltage signal (units of volts) and \( R \) is a Load resistance (unit of Ohms).
Table 4.1 and figure 4.7 show the relation between variance in noise and power received. As shown, power increases linearly as the variance in noise is increased. This is because the signal transmitted is added to noise with some variance. As the noise also has some power, the overall power received at the receiver is increased.

4.2.1.2. Bit Error Rate vs. Noise Variance for AWGN Channel

While designing the receiver, channel noise should be considered carefully because slight variations in signal due to noise cause large errors in data extraction from the received signal. Bit error rate is one of the commonly used figures of merit to estimate the performance of any digital receiver. BER is the ratio between the number of errors and total number of bits sent. It has no units, because it is the ratio of numbers. It is often expressed as a percentage. Depending on the modulation, the BER formula varies. It uses probability functions in the calculation to find the approximate BER theoretically. In Simulink® the ‘Error Rate Calculation’ block is used to calculate this. BER for BPSK modulation is calculated using equation (21):
Table 4.2. BER vs. Noise Variance for AWGN Channel

<table>
<thead>
<tr>
<th>Si.No.</th>
<th>Noise Variance</th>
<th>Bit Error rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>0.14</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0.21</td>
</tr>
<tr>
<td>4</td>
<td>1.5</td>
<td>0.25</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>0.28</td>
</tr>
<tr>
<td>6</td>
<td>2.5</td>
<td>0.30</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>0.32</td>
</tr>
<tr>
<td>8</td>
<td>3.5</td>
<td>0.33</td>
</tr>
</tbody>
</table>

In Simulink®, the Error Rate Calculation block computes the error rate of the received data by comparing it to a delayed version of the transmitted data. It takes two inputs: transmitted and received signals. It generates three outputs: error rate, number of errors detected and the total number of symbols compared.

Table 4.2 and Figure 4.8 show the relation between BER at the receiver and variance in noise. As shown, the BER increases as the variance in noise is increased. This is because the signal is highly affected when the noise level increases. When the signal is affected highly with noise, the errors in received signal increase and performance degrades.

(21)

\[ P_b = Q\left( \sqrt{\frac{2E_b}{N_0}} \right), \]

where \( P_b \) is the BER, \( E_b \) is the energy per bit, \( N_0 \) is the noise power spectral density (Watts/Hz) and \( Q(x) \) is the complementary error function:

(22)

\[ Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp \frac{-t^2}{2} \, dt. \]
4.2.1.3. BER vs. Signal to Noise Ratio for AWGN Channel

Depending on the Signal to Noise Ratio (SNR), performance of the receiver varies. The higher the SNR, the better will be the performance. In Simulink® the ‘MER Measurement’ block is used to measure the SNR of any system or channel. In this thesis, channel SNR is calculated using this block. It takes reference and received signals as inputs and gives the signal-to-noise ratio (SNR) as the output. SNR is a figure of merit in digital modulation applications. It is defined as the ratio of signal power to the noise power, often expressed in decibels (dB).

In the AWGN channel model, by varying the noise levels SNR is varied from -5 dB to 5 dB. At each instance of the SNR, the BER is noted. Figure 4.9 shows the relation between SNR and BER in AWGN channel model. It clearly shows that BER decreases linearly as the channel SNR increases. As SNR is the function of noise and signal, if signal power increases, SNR increases and the number of errors in received bits is decreased. Therefore the BER is decreased.
4.2.2. Multipath Rayleigh Fading Channel

The Rayleigh channel model creates no direct path between the transmitter and receiver but creates multiple indirect paths. These paths can have any delay and gain. In Simulink®, the ‘Multipath Rayleigh Fading Channel’ block allows users to create any number of indirect paths with different gains and delays.

4.2.2.1. Bit Error Rate vs. Signal to Noise Ratio for Rayleigh Channel

As discussed in section 4.2.1.3, the MER Measurement block is used to estimate the SNR. While varying noise levels of the channel model, the SNR is varied from -5 dB to +5 dB. For all values of SNR, the Bit Error Rates at the receiver are noted down. Figure 4.10 shows the relation between SNR and BER in Rayleigh fading channel model. As shown in the figure the BER values are decreased linearly as the SNR increases, which is similar to the AWGN channel case. As stated earlier, as the channel adds more noise to the signal, the SNR value decreases and number of errors are increased.

**Figure 4.9. BER vs. SNR for AWGN Channel**
4.2.3. Multipath Rician Fading Channel

In the Rician channel model, both Line of Sight (LOS) and Multipath components are present. In Simulink®, the ‘Multipath Rician Fading Channel’ block allows users to set Doppler shift and initial phase of LOS component. For components other than LOS, we can set different gains and delays for each path.

4.2.3.1. BER vs. $k$ factor for Rician Channel

The Rician distribution and amplitude gains are characterized by the $k$ Rice factor in Multipath Rician Fading Channel. It shows the relative strength of LOS path signal of the fading coefficient [45]. The $k$ factor is the ratio of power in the line-of-sight component to the power in other components. This ratio is expressed linearly, not in decibels. Simulink® allows users to set this value using the ‘Rician channel’ block. The $k$ factor value can be scalar or vector depending on the number of Rician fading processes.
The mathematical expression of the $k$ Rice factor is:

(23) \[ k = \frac{m}{2\sigma^2}, \]

where $m$ is the power of the dominant component and $\sigma^2$ is the local-mean scattered power.

Table 4.3 and figure 4.11 show the relation between the BER of the received signal and $k$. As shown, the BER decreases exponentially as the $k$ factor of the channel increases. The larger the value of $k$ factor, the greater the LOS component power. As the LOS component power increases, the BER decreases. Because of this relation, BER decreases as $k$ increases.

### 4.2.3.2. Bit Error Rate vs. Signal to Noise Ratio for Rician Channel

Similar to the other two channel models, the SNR is varied from -5 dB to +5 dB and the corresponding BER values at the receiver are noted down. Figure 4.12 shows the relation between BER and SNR in the Rican fading channel model. As shown, the BER decreases as the SNR increases. Again, as the signal power increases, SNR increases then the number of errors in received bits decrease which leads to a decrease in BER.
Figure 4.11. BER vs. $k$ for Rician Fading Channel

Figure 4.12. BER vs. SNR for Rician channel
4.2.4. Comparison of all Channels

In this section, a comparison between all three channel models (AWGN, Rayleigh and Rician) is performed. For the comparison, the relation BER and SNR is taken as the figure of merit. SNR is defined as the ratio of the strength of the received signal over the noise. It is measured in decibels (dB). BER is the ratio of the number of errors over the total number of received bits and has no units. Table 4.4 shows the BER for three channels for different values of SNR, whereas figure 4.13 shows a plot for these values. As seen from the figure, for all channels the BER decreases as the SNR increases. In general, BER is inversely related to SNR, that is high SNR causes low BER. As the BER increases, packet loss and delay increase. All this causes decrease in throughput. The exact relation between BER and SNR is very complicated to determine in any random channel environment. But one can determine approximate mathematical expressions using probability concepts and SNR. BER can be expressed in terms of the probability of error with the error function [14].

<table>
<thead>
<tr>
<th>SNR (dB)</th>
<th>BER in AWGN</th>
<th>BER in Rayleigh</th>
<th>BER in Rician</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5</td>
<td>0.25</td>
<td>0.54</td>
<td>0.57</td>
</tr>
<tr>
<td>-4</td>
<td>0.23</td>
<td>0.51</td>
<td>0.51</td>
</tr>
<tr>
<td>-3</td>
<td>0.22</td>
<td>0.46</td>
<td>0.44</td>
</tr>
<tr>
<td>-2</td>
<td>0.19</td>
<td>0.42</td>
<td>0.38</td>
</tr>
<tr>
<td>-1</td>
<td>0.16</td>
<td>0.38</td>
<td>0.32</td>
</tr>
<tr>
<td>0</td>
<td>0.14</td>
<td>0.21</td>
<td>0.19</td>
</tr>
<tr>
<td>1</td>
<td>0.13</td>
<td>0.17</td>
<td>0.15</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td>0.11</td>
<td>0.08</td>
</tr>
<tr>
<td>3</td>
<td>0.09</td>
<td>0.09</td>
<td>0.07</td>
</tr>
<tr>
<td>4</td>
<td>0.08</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0.01</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.4. BER vs. SNR for Three Channels
Figure 4.13 shows the relation between SNR and BER in all three channels. By implementing the different noise channels, the criterion is comparison of the variation of BER for different SNR values. As shown in the figure, the AWGN channel gives better performance for the receiver by resulting in lower BER for all SNR values. On the other hand, the Rayleigh and Rician fading channels give maximum BER. For Rician it is observed that the BER is less than Rayleigh, except in one case where the SNR is -5 dB. For higher values of SNR the BER is decreasing in all channels. The plot can be understood easily by taking one value, either BER or SNR. For example to design a receiver and to limit the BER rate less than 0.2 (2%), the minimum SNR for AWGN channel is 2dB, for Rayleigh it is 0.2dB and for Rician it’s -0.9dB. In the channel if SNR is 1, then the Bit Error Rate in the AWGN channel is 0.13 (13%), in Rayleigh is 0.17 (17%) and in Rician is 0.15 (15%). By considering these noise channel effects the receiver can be designed to achieve higher BER.
4.3. Specifications of Design

In this thesis, multi GNSS navigation system is modeled and tested using Simulink®. Navigation systems used are GPS and IRNSS. In this section design specifications of this model are discussed. Different operations on signals and observations are carried out using predefined Simulink® libraries. GPS has 24 satellites, IRNSS has 7 satellites and each of these satellites has a different PRN code. For the navigation data the Bernoulli Binary Generator block is used.

PRN codes with length of 1023 chips per millisecond and navigation data with bit rate 50 bps are considered in this design. AWGN, Rayleigh and Rician models are used in the channel section. In the receiver section two branches, one for GPS and other for IRNSS are present. These two branches perform signal acquisition. Each branch has BPF as the first block to allow only the respective navigation system signal through. Signal frequency for GPS L1 is 1575.42 MHz and for IRNSS L5 is 1176.45 MHz. The search method used in this design is parallel search technique. Different specifications for the designed mutli GNSS receiver in Simulink® are given in table 4.5.

In the design, the IRNSS transmitter looks similar to the GPS transmitter. But in real life, the transmitter in IRNSS navigation system is more complicated than GPS. In IRNSS SPS service, it transmits navigation data in L5 and S (2483.52500 MHz) frequency bands with BOC(5,2) modulation. For simplicity only the L5 signal is considered. For this reason all observations are similar for both navigation systems and therefore observations discussed earlier apply to both GPS and IRNSS. Also, this design takes some time to track the satellite and depending on the acquisition method, this time varies. Once the satellite is acquired, the receiver can extract the navigation data.

4.4. Performance Comparison

Table 4.6 shows the performance figures of merit for the designed multi GNSS navigation system. The lowest average BER is for AWGN channel than Rayleigh and Rician when compared with respect to SNR. Rician channel has 0.05 average BER with respect to \( k \) factor.
<table>
<thead>
<tr>
<th>Si.No.</th>
<th>Characteristic</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Chip Rate for GPS/IRNSS</td>
<td>1.023 MHz</td>
</tr>
<tr>
<td>2</td>
<td>PRN length for GPS/IRNSS</td>
<td>1023 chips</td>
</tr>
<tr>
<td>3</td>
<td>Navigation Data length for GPS/IRNSS</td>
<td>50 bps</td>
</tr>
<tr>
<td>4</td>
<td>Number of Satellites in GPS</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>Number of Satellites in IRNSS</td>
<td>7</td>
</tr>
<tr>
<td>6</td>
<td>Channel Models</td>
<td>AWGN, Rayleigh and Rician</td>
</tr>
<tr>
<td>7</td>
<td>Filter at Receiver</td>
<td>BPF (To allow L1 frequency)</td>
</tr>
<tr>
<td>8</td>
<td>Acquisition Method</td>
<td>Parallel Search Acquisition</td>
</tr>
<tr>
<td>9</td>
<td>GPS L1 Frequency</td>
<td>1575.42 MHz</td>
</tr>
<tr>
<td>10</td>
<td>IRNSS L5 Frequency</td>
<td>1176.45 MHz</td>
</tr>
<tr>
<td>11</td>
<td>Modulation</td>
<td>BPSK Modulation</td>
</tr>
<tr>
<td>12</td>
<td>Receiver type</td>
<td>Single channel-Dual frequency Multi GNSS receiver</td>
</tr>
</tbody>
</table>

**TABLE 4.5. Design Specifications**

<table>
<thead>
<tr>
<th>Si.No.</th>
<th>Characteristic</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Average BER for AWGN channel (wrt noise variance)</td>
<td>0.23</td>
</tr>
<tr>
<td>2</td>
<td>Average Power Received for AWGN channel (wrt noise variance)</td>
<td>28.62 dBm</td>
</tr>
<tr>
<td>3</td>
<td>Average BER for AWGN channel (wrt SNR)</td>
<td>0.14</td>
</tr>
<tr>
<td>4</td>
<td>Average BER for Rayleigh channel (wrt SNR)</td>
<td>0.27</td>
</tr>
<tr>
<td>5</td>
<td>Average BER for Rician channel (wrt SNR)</td>
<td>0.25</td>
</tr>
<tr>
<td>6</td>
<td>Average BER for Rician channel (wrt k factor)</td>
<td>0.05</td>
</tr>
</tbody>
</table>

**TABLE 4.6. Performance Comparison**
CHAPTER 5

CONCLUSIONS AND FUTURE SCOPE

5.1. Summary

Navigation is an important application in most fields. Everybody uses satellite navigation either directly or indirectly in their day to day activities. For this reason, many countries are launching their own satellite navigation systems to provide faster and accurate locations to their citizens. In open and flat areas there is a better probability to receive a higher number of satellite signals, however in urban areas and forests it is still a problem to find the exact location. There is active research going on to make use of these multi satellite signals efficiently. This thesis contributes to this research area by providing a design for multi GNSS receivers.

US government owned GPS and Indian government owned IRNSS prototypes are used in this thesis. GPS is a world famous navigation system for its global coverage and IRNSS is currently in development stage. In this project a Simulink® model for a multi GNSS receiver is designed. If we can receive and process multi GNSS signals, the process of finding location accurately will be easier. The Simulink® tool is chosen for the implementation of this thesis, for its flexibility and very intuitive user interface combined with its numerous features making design simpler, easier to understand and debug.

To reach the objective of the thesis, different navigation systems are being studied. As GPS is a common navigation system in most applications, this GNSS is considered for this thesis, whereas IRNSS is considered because the seven satellite constellation is successfully placed in April, 2016 and is in actively development stage. These two systems have two different services for civilian and military applications. GPS has L1 and L2 signals for two different applications. Similarly IRNSS has SPS and RS services. GPS L5 and IRNSS RS signal structures are known only to government authorized people. For this reason, we have considered GPS L1 and IRNSS L5 signals to test the receiver.
In this thesis we have designed a Simulink® model for the receiver that makes use of both GPS and IRNSS satellite navigations and finds the navigation data. To implement this, we have used GPS L1 and IRNSS L5 signals. A prototype for the transmitter is designed, which generates these signals using the same PRN codes in real life. The navigation data for this thesis is generated by using the ‘Bernoulli Binary Generator’ block. The receiver section consists of two branches to acquire the satellite and to extract the navigation data. The BPF created from the MATLAB® fdatool is used in the receiver section.

In the transmitter section, navigation data generation, modulo 2 operation and modulation are done in both systems. In the GPS system, the generated navigation data are modulo two added with one of the PRN codes from available 24 different PRN codes. The selection of PRN code is done using ‘Constant’ and ‘Multiport Switch’ blocks. This Multiport Switch block takes a constant value as its first input and selects one of the 24 PRN codes and sends it to the EXOR block. Both navigation data and PRN codes are modulo 2 added and then BPSK modulated with a signal frequency of 1575.42 MHz, which generates the GPS L1 signal. Similarly the IRNSS L5 signal is generated with a frequency of 1176.45 MHz.

The channel is modeled using three different distributions to describe noisy and fading channel environments. For white noise channel, AWGN model is used; for fading without LOS component Rayleigh model is used and for the fading with LOS component Rician model is used in the implementation. These three models are implemented with varying noise and varying multipath gains and the BER at the receiver is observed. All these models used in the thesis are taken from Simulink® predefined libraries.

In the receiver section, two models, one for GPS and the other for IRNSS are designed. Both of these models have a similar design to acquire and extract the satellite. In the GPS receiver, the first block is ‘GPS_BPF’, which is created using the MATLAB® fdatool. It is used to filter out all other frequencies except the L1 signal with frequency 1575.42 MHz. This filtered signal is then
BPSK demodulated and given to the acquisition block. The satellite number from which the signal has arrived is determined with which the respective PRN code can be selected. Using this duplicate PRN code, the receiver can extract the navigation data from the received signal. Depending on the channel noise and its range, the performance of the receiver varies. The same design is done for the receiver section in IRNSS navigation system.

In the observation part, a scope is connected at different places to observe and test the correctness of the design. PRN codes of GPS and IRNSS, BPSK modulated and demodulated signals, navigation data and correlation properties of PRN codes are observed during the implementation of the design. The design was modified several times until all these observations showed the expected results.

In the analysis part, the Bit Error Rate (BER) at the receiver is analyzed by taking three different noise channels. The lower the BER value, the better the receiver performance. As seen from the observations and analysis, the receiver works better in AWGN noise model and worse in the other two models i.e. Rayleigh and Rician. However, the effect of noise added in the channel also makes difference and may give different BER.

5.2. Conclusions

The designed receiver in Simulink® can receive signals, find maximum correlated satellite signal using an acquisition algorithm and extract the navigation data. This receiver is a dual frequency single channel receiver, i.e. it can receive either GPS L1 or IRNSS L5 signals and process them to extract the navigation data. The Simulink® model can be further used for preliminary tests and can form a base for making prototype hardware. The function of the receiver in different channel noise and fading conditions is tested by taking BER as the parameter. Observations and analysis from the design illustrate that this design works well even in noisy and fading channel environments.
5.3. Future Research

In the future, a hardware prototype for the proposed Simulink® model can be constructed as a next step to this research. There are certainly some features to make this project more successful. This thesis demonstrates only acquisition of the satellite. In future work, later steps like satellite tracking and pseudo range determination modules can be developed. Adding more channels in the designed receiver can increase the processing speed and can make use of more satellite signals. By adding a few more components in the receiver section, it can receive signals from other navigation systems and will be more accurate and robust. Finally, any attempt in increasing the speed of processing in the Simulink® model, will make this project more efficient. Energy-efficient design of GPS design will be a focus for obvious constraints of consumer electronics systems which are typically battery operated [39, 40].
BIBLIOGRAPHY


