Design and Simulation of Multi-Frequency Global Navigation Satellite System Receiver

Radio Frequency Front-End

A thesis presented to

the faculty of

the Russ College of Engineering and Technology of Ohio University

In partial fulfillment

of the requirements for the degree

Master of Science

Raghunath Viswanatha

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This thesis titled
Design and Simulation of Multi-Frequency Global Navigation Satellite System Receiver
Radio Frequency Front-End

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ABSTRACT

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Design and Simulation of Multi-frequency Global Navigation Satellite System Receiver Radio Frequency Front-end (125 pp.)

Director of Thesis: Chris G. Bartone

This thesis investigates several design approaches that can be employed in a Multi-frequency GNSS Receiver RF front-end for various applications. With the prospect of Galileo and GPS interoperability in the near future, many new avenues for research into the development of multi-frequency receivers have been opened. This thesis concentrates on the design of the front-end of the receiver with the assumption that the signal processing will be done in software (i.e. for a software defined radio approach). Various methods of sampling data are discussed. The software design tool Ansoft Designer® has been used to implement four design approaches that were investigated for RF front-end implementation. Each of the design approaches work with a subset of all the GPS/Galileo signals thus making that particular design approach suitable for particular applications. The various design approaches have been analyzed using Ansoft Designer® and the results are presented for the four design approaches.

Approved: _____________________________________________________________

Chris G. Bartone

Associate Professor of Electrical Engineering and Computer Science
To Janu...
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I would like to thank Ansoft LLC for providing the University Program to allow students to access high-end simulation software.
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<td>ADC</td>
<td>Analog-to-Digital Convertor</td>
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<td>AMP</td>
<td>Amplifier</td>
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<tr>
<td>ARNS</td>
<td>Aeronautical Radio Navigation Service</td>
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<tr>
<td>ASIC</td>
<td>Application Specific Integrated Circuit</td>
</tr>
<tr>
<td>B</td>
<td>Signal Bandwidth</td>
</tr>
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<td>BPF</td>
<td>Bandpass Filter</td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary Phase Shift Keying</td>
</tr>
<tr>
<td>C/A</td>
<td>Coarse/Acquisition</td>
</tr>
<tr>
<td>CL</td>
<td>Civil Long</td>
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<td>CM</td>
<td>Civil Moderate</td>
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<td>CNAV</td>
<td>Civilian Navigation</td>
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<td>CNSS</td>
<td>Compass Navigation Satellite System</td>
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<tr>
<td>EGNOS</td>
<td>European Geostationary Navigation Overlay Service</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>f_C</td>
<td>Center Frequency</td>
</tr>
<tr>
<td>f_S</td>
<td>Sampling Frequency</td>
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<tr>
<td>f_IF</td>
<td>Intermediate Frequency</td>
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<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
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<td>GAGAN</td>
<td>GPS and GEO Augmentation Navigation</td>
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<td>GEO</td>
<td>Geostationary Earth Orbit</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<td>----------</td>
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<td>GIS</td>
<td>Geographic Information Systems</td>
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<td>GLObal NAvation Satellite System</td>
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<td>Global Navigation Satellite Systems</td>
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<td>Global Positioning Systems</td>
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<td>GSO</td>
<td>Geosynchronous Orbit</td>
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<td>ICD</td>
<td>Interface Control Document</td>
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<td>IF</td>
<td>Intermediate Frequency</td>
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<td>IGSO</td>
<td>Inclined Geosynchronous Orbit</td>
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<td>IRNSS</td>
<td>Indian Radio Navigation Satellite System</td>
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<td>Kcps</td>
<td>Kilo chips per second</td>
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<td>LNA</td>
<td>Low Noise Amplifier</td>
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<td>LO</td>
<td>Local Oscillator</td>
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<tr>
<td>LPF</td>
<td>Low Pass Filter</td>
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<tr>
<td>Mcps</td>
<td>Mega chips per second</td>
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<td>MCS</td>
<td>Master Control Station</td>
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<td>MEO</td>
<td>Medium Earth Orbit</td>
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<tr>
<td>MSAS</td>
<td>Multi-functional Satellite Augmentation System</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase Locked Loop</td>
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<tr>
<td>PND</td>
<td>Personal Navigation Device</td>
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<tr>
<td>PRN</td>
<td>Pseudo Random</td>
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<tr>
<td>PVT</td>
<td>Position Velocity Time</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>--------------</td>
<td>--------------------------------------------------</td>
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<tr>
<td>Q</td>
<td>Quality factor</td>
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<tr>
<td>QZSS</td>
<td>Quazi-Zenith Satellite System</td>
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<tr>
<td>RAIM</td>
<td>Receiver Autonomous Integrity Monitoring</td>
</tr>
<tr>
<td>RC</td>
<td>Replacement Code</td>
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<tr>
<td>RF</td>
<td>Radio Frequency</td>
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<tr>
<td>RHCP</td>
<td>Right Hand Circularly Polarized</td>
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<td>SBAS</td>
<td>Satellite Based Augmentation System</td>
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<td>SDR</td>
<td>Software Defined Radio</td>
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<td>SIS</td>
<td>Signal-in-Space</td>
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<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
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<td>SV</td>
<td>Space Vehicle</td>
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<td>TCXO</td>
<td>Temperature Controlled Crystal Oscillator</td>
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<td>USA</td>
<td>United States of America</td>
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<tr>
<td>VCO</td>
<td>Voltage Controlled Oscillator</td>
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<td>WAAS</td>
<td>Wide Area Augmentation System</td>
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1 INTRODUCTION

Initially developed in the early 1970’s by the Government of the United States of America (USA), the Global Positioning System (GPS) is a satellite-based navigation technology. Its primary focus was to provide precise positioning, navigation and timing services for military use, and it was extended to civilian applications. It is the most fully operational Global Navigational Satellite System (GNSS). However many nations are joining the movement to provide precision positioning, navigation and timing services [1].

In the early 1970s almost in parallel with USA, Russia was developing its own counterpart to GPS, namely GLObal NAvigation Satellite System (GLONASS). Though it did provide robust positioning services for a number of years, about seven years ago the GLONASS constellation was reduced to seven satellites [1].

Since then the international GNSS community has seen several advancements in the development of satellite based navigation systems. To name a few, some of the important entrants have been Europe’s Galileo with the launch of its first experimental GNSS satellite, GIOVE –A as well as China’s Compass with its three initial Beidou satellites launch [1]. Other countries still in the early stages of development of their satellite technology are India with its Indian Radio Navigation Satellite System (IRNSS) and Japan with its Quasi-Zenith Satellite System (QZSS). The advancement of GLONASS is
also not too far behind as the Russian government is investing time and money into its rebuilding and modernization [1].

Each of these various systems have their own levels of detail and complexity in regards to signal structure, satellite design etc, but for all GNSS systems, the fundamental segments remain the same. They are broadly classified as Space, Control and User Segments.

The Space Segment comprises the satellites that are in orbit and are continuously transmitting signals in space. The definitions of the signals under scrutiny in this research are defined in greater detail in Chapter 2. Each of the different GNSS systems has their independent satellite orbit configurations as summarized in Table 1-1.

The Control Segment comprises Master Control Stations (MCS) that monitor satellite orbits, satellite health and maintain time, update satellite navigation messages, and command small corrective satellite maneuvers, to name some of its principal functions. The Control Segment also includes monitor stations and telemetry channels to communicate to the satellite.

The User Segment comprises the receivers that have been developed to acquire and track satellite signals and in turn provide positioning, navigational and timing capabilities [2].
As the longest operational GNSS system, GPS has since its advent undergone constant improvement in the accuracy of the positioning calculations at the user segment level and control segment. At the user segment level, there has also been extensive research in trying to reduce the influence of major error causing sources such as atmospheric delay, multipath and jamming. At the control segment level, six new monitoring stations were added in 2005 hence providing a greater visibility of the GPS constellation [3].

Some information on the various constellations is shown in Table 1-1:

**Table 1-1: Space Constellation Parameters [1]**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Galileo</th>
<th>GPS</th>
<th>GLONASS</th>
<th>Compass</th>
<th>QZSS</th>
<th>IRNSS</th>
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<tr>
<td>Constellation</td>
<td>Walker MEO (27/3 orbits)</td>
<td>MEO (24/6 orbits)</td>
<td>MEO (24/3 orbits)</td>
<td>GEO (5), MEO (27), IGSO (3)</td>
<td>GSO (3)</td>
<td>GEO (3), GSO (4)</td>
</tr>
<tr>
<td>Inclination</td>
<td>56°</td>
<td>55°</td>
<td>64.8°</td>
<td>55°</td>
<td>45°</td>
<td>29°</td>
</tr>
<tr>
<td>Semi Major Axis</td>
<td>29601.297 km</td>
<td>26559.7 km</td>
<td>25440 km</td>
<td>27840 km</td>
<td>42164.0 km</td>
<td>42164.0 km</td>
</tr>
</tbody>
</table>

MEO – Medium Earth Orbit

GEO – Geostationary Earth Orbit

GSO – Geo-Synchronous Orbit

IGSO – Inclined Geo-Synchronous Orbit
1.1 Modernization

The last decade has seen major advances in the international GNSS community. A brief summary of the updates that have taken place within the various satellite system structures are presented.

1.1.1 GPS

In the last decade one of the most significant changes to GPS has been the removal of Selective Availability thus eliminating the intentional degradation of the civil signal. There have also been improvements in the space segment, the first being the launch of the Block IIR satellites in 1997 that boast of reprogrammable satellite processors enabling problem fixes and upgrades in flight [3]. The Block IIR satellites were modernized (i.e., IIR-M) to radiate the new civil L2C signal at 1227.60 MHz. The next planned upgrade is the launch of the Block IIF satellite that has extended life, faster processors as well as the introduction of the L5 signal at 1176.45 MHz [3]. Additionally, testing of the L5 signal on the Wide Area Augmentation System (WAAS) satellite is underway [4]. A new civilian L1C signal at 1575.42 MHz will be introduced with the launch of Block III satellites. It is the result of collaboration between Europe and USA to provide a compatible and interoperable signal on L1 frequency [4].
Each new signal such as L2C, L5 and L1C whose spectra are shown in Figure 1-1 [5] offers its own set of advantages but over all the major advantage from these new signals is better accuracy due to longer codes, higher chipping rate and/or stronger signal with more powerful error correction.

![Figure 1-1: Newly Introduced Civil GPS Signals](image)

Along with the space segment, six new monitoring ground stations were added to the control segment in 2005 [3].

1.1.2 Galileo

Galileo is the latest addition to GNSS and is currently under development by the European Space Agency (ESA) [6]. It is expected to be fully operational by 2012 [1] with a constellation of 30 satellites (27 fully operational and 3 standby) and transmitting on three different frequencies, E1 – 1575.42 MHz, E6 – 1278.75 MHz and E5 – 1191.795 MHz (E5a – 1176.45 MHz and E5b – 1207.14 MHz).
1.1.3 GLONASS

The choice of Frequency Division Multiple Access (FDMA) design and lack of enough satellites caused GLONASS to suffer from low utility [4]. In 2003 Russia decided to join USA and Europe in plans of modernizing their system by adding additional satellites to their space segment. The addition of a new civilian signal L3 located between 1164 MHz and 1215 MHz is also in the works [4].

1.1.4 Compass

Currently under development by China is their own GNSS called Compass Navigation Satellite System (CNSS) or Compass. Currently the space segment of Compass is planned to consist of 5 Geostationary Earth Orbit (GEO) and 30 Medium Earth Orbit (MEO) satellites transmitting four different signals [7].

1.1.5 GNSS Augmentation

Satellite Based Augmentation System (SBAS) satellites in geo-stationary orbits are used to transmit pseudorange corrections, navigation integrity and satellite health information by using signals similar in format to that being transmitted by the GNSS. The WAAS transmitting at the L1 frequency is an SBAS covering North America.
Other SBAS architectures under development are the European Geostationary Navigation Overlay Service (EGNOS), Japan’s Multi-Functional Satellite Augmentation System (MSAS), China’s Beidou and India’s GPS and GEO Augmentation Navigation (GAGAN) [1] [4].

1.2 Interoperability

Most new civilian signals in the GNSS spectrum as seen in Figure 1-2 [5] [8] [9] share their frequencies with one another. Hence it is important to make sure that one signal does not interfere with the other. If used together, they provide better performance and accuracy than when used individually.

![GNSS Signal Spectrum](image)

*Figure 1-2: GNSS Signal Spectrum*

Keeping this viewpoint in mind, these new signals sharing a frequency band are being designed to be interoperable. Galileo’s E1 and GPS L1C are currently being developed
by USA and European Union (EU) under agreement [10] to provide a common baseline signal with optimized signal structure (i.e., MBOC modulation [5]) for maximum performance. Similarly, the idea of interoperability has also been extended to Galileo E5a and GPS L5 signals. This will allow for increased research and development in the user segment to capitalize on the interoperability between GPS and Galileo signals.

1.3 Motivation and Scope of the Project

With the ongoing growth and development in the space segment of the GNSS community, it is only natural that the user segment follows with similar advances in receiver technology that can capitalize on this growth. As new signals with higher chipping rates and wider bandwidths are introduced, the new GNSS receivers should be able to process and acquire these multiple signals simultaneously.

This project rests on the merits of these technical advances and tries to explore the various methods that can be applied to the design and development of a Multi-frequency GNSS Receiver. Specifically this work evaluates the different approaches that can be used to implement the GNSS Radio Frequency (RF) front-end. To aid in this design, two software design resources, namely Matlab® and the Ansoft Designer® were used.

A trade study has been performed between the following:

- The direct sampling, and down-conversion & sampling methods,
- Choice of signals,
- Low cost, low power design options.
2 GNSS SIGNALS IN SPACE

This chapter provides the basic description of the GPS and Galileo signals that have been considered for the Multi-frequency GNSS receiver being designed.

2.1 Legacy & New Civil GPS Signals

Until recently there were only two GPS signals being broadcast, one at L1 1575.42 MHz and the other at L2 1227.60 MHz. While both signals transmit the restricted precision (encrypted) or P(Y) code, only the L1 signal transmits the civilian Coarse/Acquisition or C/A code. By the year 2015, due to ongoing modernization efforts, there will be a total of three new civilian signals - L1C, L2C and L5 broadcast at 1575.42 MHz, 1227.60 MHz and 1176.45 MHz respectively. All of these civilian signals are under consideration for the design approaches detailed in Section 4.2. The legacy and new GPS signal spectra including the signals with restricted access (i.e., L1 P(Y), L1M, L2 P(Y) and L2M) are shown in Figure 2-1 [5] [8] [9].
2.1.1 Legacy L1 Signal

The Legacy L1 signal is fully defined in the interface specification document IS-GPS-200 [11]. A convenient expression for defining the L1 signal for the kth satellite is:

$$S_{L1}^{k}(t) = \sqrt{2P} D^k(t)x^k(t)\cos(2\pi f_{L1}t + \theta_{L1})$$  \hspace{1cm} \text{Eq 1}$$

This equation is defined as the product of 4 terms: $\sqrt{2P}$ is the amplitude, $D(t)$ is the navigation data, $x(t)$ is the spread spectrum code and $\cos(2\pi ft + \theta)$ is the RF carrier [12].

The major components of the signal are defined as follows:

- A sinusoidal carrier signal, $\cos(2\pi ft + \theta)$ at a frequency of 1575.42 MHz.
- The C/A code $x(t)$ is a unique sequence of 1023 bits called chips and is repeated every millisecond. This translates to a distance for each chip of 300 m. The chipping rate of the C/A code is 1.023 MHz (also Mcps) [2].
- Navigation data $D(t)$ is a binary coded message transmitted at 50 bits per second with bit duration of 20 milliseconds. These data messages contain information on various satellite parameters such as satellite health status, ephemeris, satellite...
clock error and almanac that contains reduced precision data for the entire constellation [2].

Each spreading code is combined with the binary navigation data with modulo-2 addition. The composite binary addition is then modulated with the carrier using BPSK or Binary Phase Shift Keying. The modulation of the carrier by a binary code spreads the signal energy over a wide frequency band i.e., 2.046 MHz (null-to-null bandwidth) for the L1 C/A code signal. This unique property makes the spread spectrum signal desirable for communication as well as navigation [2].

2.1.2 L2 Civilian Signal

The L2C signal is defined in the interface specification document IS-GPS-200 [11]. The signal structure for the kth satellite can be described as:

\[ S_{\text{L2}}(t) = \sqrt{2P} F\{D_{\text{L2}}(t)\} RC_{\text{L2}}(t) \cos(2\pi f_{\text{L2}} t + \theta_{\text{L2}}) \]  

- Eq 2

This equation is a product of 4 terms: \( \sqrt{2P} \) - the amplitude, \( F\{D(t)\} \) – \( \frac{1}{2} \) convolutional coded navigation data \( D(t) \), \( RC(t) \) is the spread spectrum code called replacement code and \( \cos(2\pi ft + \theta) \) is the RF carrier [12].

For the Block IIR-M, IIF and subsequent blocks of Space Vehicles (SV) two Pseudo Random (PRN) code components – the L2 Civil Moderate (L2 CM) and the L2 Civil Long (L2 CL) will be transmitted. The L2 CM code is 20 milliseconds in length with a
chipping rate of 511.5 Kcps. The L2 CL code is 1.5 seconds with a chipping rate of 511.5 Kcps.

The navigation data (also called CNAV – Civilian Navigation data) $D_{L2}(t)$ is updated for Block IIR-M, IIF and subsequent blocks of SVs. The $D_{L2}(t)$ is a 25 bps data stream that is coded by a rate $\frac{1}{2}$ convolutional coder. The resulting 50 symbols per second (sps) stream is modulo-2 added to the L2-CM code. The resultant signal is combined with the L2-CL code using chip-by-chip time division multiplexing method (alternating between L2-CM data and L2-CL chips) forming the replacement code. This multiplexed bit train with a resulting chipping rate of 1.023 Mcps is used to BPSK modulate the L2 carrier [12].

2.1.3 L5 Civilian Signal

A new civilian signal to be transmitted at $L_5 = 1176.45$ MHz on the Block IIF and subsequent blocks of SVs. This signal is fully defined in the interface specification document IS-GPS-705 [13]. The following is the mathematical equation for the $k^{th}$ satellite signal structure:

$$S_{L5}^k(t) = \sqrt{2P} F\{D_{L5}(t)\} N H_{10}(t) g_1^k(t) \cos(2\pi f_{L5} t + \theta_{L5}) +$$

$$\sqrt{2P} N H_{20}(t) g_2^k(t) \sin(2\pi f_{L5} t + \theta_{L5}) \quad [12]$$

$S_{L5}^k(t)$ is the equation for the L5 signal with two components. Both components with amplitudes $\sqrt{2P}$ are civilian signals. The L5 signal has two carrier components in
quadrature phase with each other. Each component is BPSK modulated by a separate bit train [13].

The PRN codes of the two components of the L5 signal are denoted as \( I_5 (g_1(t) \cos(2\pi f t + \theta)) \) and \( Q_5 (g_2(t) \sin(2\pi f t + \theta)) \). Each code (i.e., \( g_1(t) \) and \( g_2(t) \)) is 10230 chips long and has a chipping rate of 10.23 MHz. These codes are generated as the modulo-2 sum of two sub-sequences \( X_A \) and \( X_B \) with lengths of 8190 and 8191 chips [13].

\( D_{L5}(t) \) is the L5 CNAV navigation data at 50 bits per second. Forward error correction is applied to this data stream and the resultant symbol rate is 100 sps. This resultant bit stream is modulo-2 added to the in-phase component of the code of the signal only; the resultant is used to modulate the in-phase component of the L5 carrier signal. This data is very similar to that modulated on to the L2C signal. The L5 quadrature phase carrier has no navigation data. The signal has a null-to-null bandwidth of 20.46 MHz centered on the L5 frequency of 1176.45 MHz with a protected 24 MHz channel [12] [13].

Neumann-Hofman codes \( NH_{10} \) and \( NH_{20} \), which are 10 milliseconds and 20 milliseconds long respectively, also modulate the in-phase and quadrature phase channels at 1.023 Mcps thus increasing the effective code lengths to 102,300 and 204,600 chips for \( g_1(t) \) and \( g_2(t) \) respectively [12] [13].
2.2 Galileo Signal Structure

Three carrier signals are currently planned for the Galileo satellite constellation: E1, E5 and E6 at 1575.42 MHz, 1191.795 MHz and 1278.75 MHz respectively, where only E1 and E5 carry open service signals. Their signal spectra are depicted in Figure 2-2 [5] [8] [9]. E5a is similar to the L5 signal structure thus providing opportunity for interoperability.

![Figure 2-2: New Galileo Signal Spectra](image)

2.2.1 E5 Signal Structure

The E5 centered at 1191.795 MHz signal is comprised of E5a and E5b components. The E5 signal components are generated as stated in the Galileo Interface Control Document (ICD) [14] as follows:

- $e_{E5a-I}$ from the navigation data stream $D_{E5a-I}$ modulated with the unencrypted ranging code $C_{E5a-I}$.
- The pilot channel $e_{E5a-Q}$ from the unencrypted ranging code $C_{E5a-Q}$. 
- $e_{E5b-1}$ from the navigation data stream $D_{E5b-1}$ modulated with the unencrypted ranging code $C_{E5b-1}$.
- The pilot channel $e_{E5b-Q}$ from the unencrypted ranging code $C_{E5b-Q}$.

The signal structure for E5 is as follows [14]:

$$
e_{E5a-I}(t) = \sum_{i=-\infty}^{+\infty} [c_{E5a-I}, i]_{L_{E5a-I}} \cdot d_{E5a-I}, i]_{DC_{E5a-I}} \cdot rect_{T_{C,E5a-I}}(t - i \cdot T_{C,E5a-I}) [14]$$ - Eq 4

$$
e_{E5a-Q}(t) = \sum_{i=-\infty}^{+\infty} [c_{E5a-Q}, i]_{L_{E5a-Q}} \cdot rect_{T_{C,E5a-Q}}(t - i \cdot T_{C,E5a-Q}) [14]$$ - Eq 5

$$
e_{E5b-I}(t) = \sum_{i=-\infty}^{+\infty} [c_{E5b-I}, i]_{L_{E5b-I}} \cdot d_{E5b-I}, i]_{DC_{E5b-I}} \cdot rect_{T_{C,E5b-I}}(t - i \cdot T_{C,E5b-I}) [14]$$ - Eq 6

$$
e_{E5b-Q}(t) = \sum_{i=-\infty}^{+\infty} [c_{E5b-Q}, i]_{L_{E5b-Q}} \cdot rect_{T_{C,E5b-Q}}(t - i \cdot T_{C,E5b-Q}) [14]$$ - Eq 7

Table 2-1 provides definitions for all the parameters used in the above equations.
Table 2-1: Galileo Signal Description Parameters [14]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Explanation</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_x$</td>
<td>Carrier Frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$P_x$</td>
<td>RF- Signal Power</td>
<td>W</td>
</tr>
<tr>
<td>$L_{X-Y}$</td>
<td>Ranging code repetition period</td>
<td>s</td>
</tr>
<tr>
<td>$T_{C,X-Y}$</td>
<td>Ranging code chip length</td>
<td>s</td>
</tr>
<tr>
<td>$T_{S,X-Y}$</td>
<td>Subcarrier period</td>
<td>s</td>
</tr>
<tr>
<td>$T_{D,X-Y}$</td>
<td>Navigation Message symbol duration</td>
<td>s</td>
</tr>
<tr>
<td>$R_{C,X-Y}$</td>
<td>$=1/ T_{C,X-Y};$ code chip rate</td>
<td>Hz</td>
</tr>
<tr>
<td>$R_{S,X-Y}$</td>
<td>$=1/ T_{S,X-Y};$ Subcarrier frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$R_{D,X-Y}$</td>
<td>$=1/ T_{D,X-Y};$ Navigation message symbol rate</td>
<td>Hz</td>
</tr>
<tr>
<td>$S_X(t)$</td>
<td>Signal pass-band representation</td>
<td></td>
</tr>
<tr>
<td>$C_{X-Y}(t)$</td>
<td>Binary (NRZ modulated) ranging code</td>
<td></td>
</tr>
<tr>
<td>$D_{X-Y}(t)$</td>
<td>Binary (NRZ modulated) navigation message signal</td>
<td></td>
</tr>
<tr>
<td>$sc_{X-Y}(t)$</td>
<td>Binary (NRZ modulated) subcarrier</td>
<td></td>
</tr>
<tr>
<td>$e_{X-Y}(t)$</td>
<td>Binary NRZ modulated navigation signal component including code, sub-carrier if available and navigation message data (if available) ($=C_{X-Y}(t). sc_{X-Y}(t). D_{X-Y}(t)$);</td>
<td></td>
</tr>
<tr>
<td>$s_a(t)$</td>
<td>Normalized baseband signal ($=s_{X,I}(t) + j.s_{X,Q}(t))$ (unit mean power)</td>
<td></td>
</tr>
<tr>
<td>$c_{X,Y,k}$</td>
<td>‘$k^{th}$’ Chip of the ranging code</td>
<td></td>
</tr>
<tr>
<td>$d_{X,Y,k}$</td>
<td>‘$k^{th}$’ symbol of the navigation message</td>
<td></td>
</tr>
<tr>
<td>$DC_{X-Y}$</td>
<td>$=T_{D,X}/T_{C,X};$ number of code chips per symbol</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>i</td>
<td>_L$</td>
</tr>
<tr>
<td>$[i]_{DC}$</td>
<td>Integer part of $i/DC$</td>
<td></td>
</tr>
<tr>
<td>$\text{rect}_T(t)$</td>
<td>Function ‘rectangle’, which is equal to 1 for $0 &lt; t &lt; T$, and equal to 0 elsewhere</td>
<td></td>
</tr>
</tbody>
</table>
where,

X - Respective Carrier (E5, E5a, E5b or E1)

Y - Respective signal component or signal channel (B, C, I, Q)

The composite E5 signal is generated with AltBOC modulation of side-band sub-carrier rates \( R_{sE5}=1/T_{sE5} = 15.345 \text{ MHz} \ (15 \times 1.023 \text{ MHz}) \) using the following equation:

\[
\begin{align*}
S_{E5}(t) & = \frac{1}{2 \cdot \sqrt{2}} \cdot (e^{j \cdot E_{5a-I}}(t) + j \cdot e^{j \cdot E_{5a-Q}}(t)) \cdot [s_c E_{5-S}(t) - j \cdot s_c E_{5-S}(t - T_{s,E5}/4)] + \\
& \frac{1}{2 \cdot \sqrt{2}} \cdot (e^{j \cdot E_{5b-I}}(t) + j \cdot e^{j \cdot E_{5b-Q}}(t)) \cdot [s_c E_{5-S}(t) + j \cdot s_c E_{5-S}(t - T_{s,E5}/4)] + \\
& \frac{1}{2 \cdot \sqrt{2}} \cdot (e^{j \cdot E_{5a-I}}(t) + j \cdot e^{j \cdot E_{5a-Q}}(t)) \cdot [s_c E_{5-P}(t) - j \cdot s_c E_{5-P}(t - T_{s,E5}/4)] + \\
& \frac{1}{2 \cdot \sqrt{2}} \cdot (e^{j \cdot E_{5b-I}}(t) + j \cdot e^{j \cdot E_{5b-Q}}(t)) \cdot [s_c E_{5-P}(t) + j \cdot s_c E_{5-P}(t - T_{s,E5}/4)]
\end{align*}
\]

[14] - Eq 8

E5a does not have a sub carrier and transmits both the pilot and data channels at 10.23 Mcps resulting in 20.46 MHz null-to-null bandwidth. The navigation data streams at a symbol rate of 50 sps.
2.2.2 E1 Signal Structure

The E1 signal components are generated as stated in the Galileo ICD [14] as follows:

- $e_{E1-B}$ from the F/NAV navigation date stream $D_{E1-B}$ modulated with the ranging code $C_{E1-B}$ and the sub-carrier $sc_{E1-B}$.

- The pilot channel $e_{E1-C}$ from the ranging code $C_{E1-C}$ modulated with the sub-carrier $sc_{E1-C}$.

The B and C components of the E1 signal are generated as stated in the Galileo ICD [14] as follows:

$$e_{E1-B}(t) = \sum_{i=-\infty}^{+\infty} c_{E1-B}[i] d_{E1-B}[i] \cdot rect_{T_{C,E1-B}}(t-i \cdot T_{C,E1-B}) \cdot \text{sign}[\sin(2\pi R_{S,E1-B} \cdot t)]$$ \[Eq 9\]

$$e_{E1-C}(t) = \sum_{i=-\infty}^{+\infty} c_{E1-C}[i] \cdot rect_{T_{C,E1-C}}(t-i \cdot T_{C,E1-C}) \cdot \text{sign}[\sin(2\pi R_{S,E1-C} \cdot t)]$$ \[Eq 10\]

The signal parameters are as defined in
Table 2-1. The composite E1 signal is given as:

$$S_{E1}(t) = \frac{1}{\sqrt{2}} [e_{E1-B}(t) - e_{E1-C}(t)] \quad \text{[14]} \quad \text{Eq 11}$$

Galileo satellites transmit ranging codes for the E1 signal with a chipping rate of 1.023 Mcps and sub-carrier rate of 1.023 MHz. Navigation data is streamed only on Channel B with a symbol rate of 250 sps.

This is just a brief summary of the signal structure for the various GPS and Galileo signal structures. The references section lists the Signal-in-Space (SIS) interface specification for GPS L1/L2 at [11] and L5 at [13] and ICD for Galileo at [14] for in depth details of the various characteristics of the signals.
3 GNSS RECEIVER

The focus of this thesis research was the design of the front-end of a GNSS receiver, particularly a combined GPS/Galileo receiver. This chapter presents the various methodologies considered for the design of the RF front-end.

3.1 Combined GPS/Galileo Receiver

The 2004 agreement between EU and USA [10] allowed for the development of signals for the GPS and Galileo that are interoperable as well as compatible. The focus here is only on the design of a combined GPS/Galileo receiver. There are several advantages to pursuing this approach. To name a few:

- **Accuracy**: The interoperability of signals allows for improved accuracy in the Position, Velocity and Time (PVT) solution.

- **Greater Availability**: The receiver can seamlessly transition from a GPS signal to a Galileo signal for PVT calculations depending on coverage provided by the constellation that is visible at the time. This allows for uninterrupted service for the user without creating any restrictions on user location.

- **Receiver Autonomous Integrity Monitoring (RAIM) computation integrity**: Increased integrity due to better availability when a combined constellation is used for RAIM computations.
This research focuses on the RF front-end design for a combined GPS/Galileo GNSS receiver using a Software Defined Radio (SDR) approach.

3.2 Software Defined Radio

The concept of a SDR has gained immense popularity due to the evolution of high speed Analog-to-Digital Converters (ADC) that can digitize radio signals and increase the computational power of signal processors. The ability to handle large amounts of data and process them in software is improving by the day. Thus the need for using Application Specific Integrated Circuits (ASIC) to perform baseband processing is diminished in a SDR approach [15].

The three main sub-systems of a GNSS receiver are:

- Antenna
- RF Front-end
- Baseband Processor.

*Antenna:* The antenna subsystem is designed such that it can receive Right Hand Circularly Polarized (RHCP) GNSS signals. It is typically followed by a Low Noise Amplifier (LNA), which essentially sets the noise figure of the receiver. One of the important design criteria is to choose an antenna that can receive multiple GNSS signals.
*RF Front-end:* The RF front-end essentially filters the interference signals and amplifies the RF signal(s) of interest to the level that is required by the ADC for digitization. The various signals of interest impose greater restrictions on the bandwidth of the front-end as each signal has wide band considerations that need to be adhered to. Digitization of the signal also proves to be a major criterion in the design of the ADC.

*Baseband Processor:* The baseband processor receives the digitized signal, which is output from the front-end ADC, then acquires and tracks the signals from each of the visible satellites to eventually provide the user with a PVT solution. The major consideration here is the processing of the digitized signals regardless of whether they were sampled either independently or in a single channel to provide the user with a PVT solution suitable for the application. Since most of the baseband processing is defined in software, it gives the user an opportunity to update software parameters allowing the same baseband processor to be used across different RF front-ends.

The focus for this project is only on the RF front-end design. The antenna and the baseband processing are discussed in detail in Chapter 4.

### 3.3 RF Front-end Design

There are two major approaches that can be used for RF front-end design:

- Superheterodyne approach
Direct digitization or Direct RF sampling.

The approaches that are not discussed here but are worth mentioning are:

- Direct Conversion [16] or Zero Intermediate Frequency (IF) Sampling, where the RF is directly down-converted to zero IF using the Superheterodyne approach.
- Digital Down Conversion [17] which is an extension to direct RF sampling where the sampled data is further down-converted to a digital IF at the baseband processor level.

3.3.1 Superheterodyne Approach

In the superheterodyne method there are three main elements: a local oscillator (LO), a mixer and a filter. The LO produces a signal at frequency \( f_{\text{LO}} \) which is typically close to the frequency \( f_C \) of the incoming RF signal. The mixer takes the input RF signal and the LO signal and multiplies them to produce two frequency translated components one at frequency \( f_C + f_{\text{LO}} \) and the other at \( f_C - f_{\text{LO}} \) [18]. The filter is then used to select one of the frequency components and for a down-conversion application \( f_C - f_{\text{LO}} \) is typically selected.

This down conversion of the input signal to an IF can be achieved in either a single stage or multiple stages. Since the IF is low (typically in the 10’s of MHz range), the ADC sampling frequency could be selected based on Nyquist sampling:

\[
f_s > 2(f_{\text{IF}} + B/2)
\]

\[\text{Eq 12}\]

where
$f_{IF}$ is the IF the input signal is down converted to,

$f_s$ is the sampling frequency, and

$B$ is the bandwidth of the signal of interest where the out of band signal power has been limited to a predefined level (e.g. -40 dB down) to prevent aliasing.

*Figure 3-1* depicts a multi-stage and a single-stage RF down conversion respectively.

*Figure 3-1: Superheterodyne Down Conversion* (a) Multi Stage (b) Single Stage

where

AMP – Amplifier

LPF – Low Pass Filter

BPF – Band Pass Filter

LO – Local Oscillator
The superheterodyne technique offers many advantages, foremost being:

- Every stage of down conversion is sensitive to a narrow range of frequencies.
- It is easier to design filters with a high Quality Factor (Q) at IF than at RF for a given information bandwidth thus providing higher selectivity.
- Analog components are easily available at IF rather than at RF.
- The sampling frequencies are relatively low (in 10’s of MHz range) and a single channel is used to digitize one signal, thus leading to less complicated baseband processing.
- It is a tried, tested and proven technique.

The primary disadvantage of the superheterodyne is the addition of spurious signals by the mixer from image frequencies which when passed through the mixer, for a given local oscillator frequency, $f_{LO}$, will produce the same IF as the frequency of interest, $f_c$. The image frequency is given by

$$f_{image} = \begin{cases} f_c + 2f_{IF}, & \text{if} \quad f_{LO} > f_c \\ f_c - 2f_{IF}, & \text{if} \quad f_{LO} < f_c \end{cases}$$  - Eq 13

where,

- $f_c$ is the center frequency of the frequency of interest
- $f_{IF}$ is the resulting intermediate frequency, output of the mixer.

For Example, at the L1 carrier of 1575.42 MHz, if an IF of 70 MHz is desired, an LO of 1505.42 MHz would be selected. By Eq 13, the image frequency can be computed as
1575.42 MHz – (2 x 70 MHz) = 1435.42 MHz. Hence a real signal at 1435.42 MHz would get down converted to an IF of 70 MHz.

Careful design of the RF filter before the mixer, also called as the preselector, is needed to protect the receiver from the image frequency. The selection of the additional stages depends on how much protection/shielding is needed from the adjacent channels and the amplification needed to bring the signal up to the level needed by the ADC [15]. Additionally the mixer component has limited linear dynamic range and produces additional spurious signals at IF output.

3.3.2 Direct RF Sampling

In this technique, the output of the antenna is directly sampled at the RF frequency. This can be done in the two following ways:

(a) Nyquist Sampling

In Nyquist sampling the sampling frequency $f_S$ is selected such that it is no less than twice the highest frequency component of the RF signal [19] as computed in $Eq\ 12$.

$$f_S > 2(f_C + B/2)$$

where,

$f_C$ is the center frequency

B is the signal bandwidth where the out of band signal power has been limited by the bandpass filter (BPF) to a predefined level (e.g. -40 dB down).
This technique results in very high sampling rates requiring a high speed ADC, which increases the complications in baseband processing due to the overwhelming amount of data to process [15], increase in power consumption due to the use of high speed ADCs thus leading to high implementation costs.

(b) Bandpass Sampling

The bandpass sampling frequency $f_s$ is computed per the following criteria [15] [20]:

\[ f_s > 2 \times B, \quad \text{Eq 14} \]

where, $B$ is the signal bandwidth where the out of band signal power has been limited to a predefined level (i.e., -40 dB down). Additionally, the sampled signals will be aliased to an intermediate frequency of $f_{IF}$ which is computed as

\[
f_{IF} = \begin{cases} 
\text{rem}(f_c, f_s), & \text{if } \text{fix}\left[\frac{f_c}{f_s/2}\right] \text{ is even} \\
 f_s - \text{rem}(f_c, f_s), & \text{if } \text{fix}\left[\frac{f_c}{f_s/2}\right] \text{ is odd}
\end{cases}
\]

[15] \quad \text{Eq 15}

Here ‘fix’ and ‘rem’ are defined functions where ‘fix’ rounds the value of $\frac{f_c}{f_s/2}$ to the nearest integer towards zero and ‘rem’ gives a remainder after the division of $f_c$ by $f_s$. Care must be taken to make sure $f_s$ is selected in such a way that the following condition holds true for $f_{IF}$:

\[
\frac{B}{2} < f_{IF} < \frac{f_s - B}{2}
\]

[15] \quad \text{Eq 16}
It is crucial that the sampling frequency chosen translates the entire signal bandwidth B to the resulting IF in the sampled bandwidth $f_S/2$ or else there is greater chance that the information band may fold onto itself causing aliasing.

There are various advantages to the Direct RF sampling technique, some of the more important being:

- Minimal number of analog components required in the front-end design.
- Eliminating the mixer in the system eliminates the possibility of an image frequency getting down-converted to the IF by the mixer and also any other unwanted spurious signals leaking into the resultant IF signal through it.
- For a given sampling frequency, the RF front-end with a single ADC can be used to sample multiple signals provided the resulting intermediate frequencies pass the criteria given above and in conjunction with the following criteria:

$$\left| f_{IF_a} - f_{IF_b} \right| > \frac{B_a - B}{2} \quad \text{[15]}$$  -Eq 17

where,

- $a = 2\ldots n$
- $b = 1\ldots(a-1)$
- $n =$ total number of signals being sampled.
The Direct RF sampling techniques are not without its challenges, some of the most significant being:

- Increased computational burden at the baseband processing level when multiple signals are down converted using a single ADC.
- It is difficult to design a filter with high Q at RF with a given bandwidth requirement compared to at an IF.
- Since high amount of gain at the RF is required to bring the input RF signal up to the level needed by the ADC, significant care should be taken to isolate the RF input to the system and analog output which is used as input to the ADC [21].
- Significant loss in Signal-to-Noise Ratio (SNR) due to aliasing and clock jitter [22].
- The power constraints of a GNSS receiver greatly depend on the application (for e.g. handheld applications versus avionics). A single ADC to sample an RF signal needs a wide analog bandwidth at least to accommodate the signal and the technology used in such ADCs is flash based (e.g. Maxim’s MAX106 [23]) which consumes several watts of power to activate 6 to 8 bits [21]. With a multi-frequency receiver, using either a single or multiple high speed ADCs based on the application, the power requirements for the receiver can greatly increase.
- When a single ADC is used to sample multiple signals, interference on one signal (e.g. jamming) can corrupt the output of ADC.
- The preselector (first filter after the antenna) needs careful consideration in order to provide adequate protection against image frequencies which are defined as the
frequency component $f_M$ which samples down to the same IF, $f_{IF}$, as the signal of interest $f_C$ defined over a signal bandwidth $B$ for a given bandpass sampling frequency $f_S$.

In the following chapter the design of the RF front-end based on Direct RF sampling is used. The assumptions made about the antenna necessary to provide an input to the RF front-end are also discussed briefly.
4    GNSS RF FRONT-END DESIGN

As discussed in Section 3.2, a GNSS receiver consists of three main components. The first component is the antenna. The following section briefly describes the assumptions made in order for the antenna to receive multiple GNSS frequencies.

4.1   Antenna

A typical single-frequency antenna consists of a receiving element, an LNA and a bias-T which powers the amplifier. *Figure 4-1* illustrates an example of single-frequency antenna subsystem. The design can be extended to multiple frequencies and be implemented in two different configurations as explained in the following section.

4.1.1   Multi-Stage Antenna

Multiple antenna elements designed to receive a particular frequency with the appropriate bandwidth requirements is shown in *Figure 4-2*. Each antenna element is used to receive a particular signal frequency of interest. For the current project n is set to 3. Here the signal from each individual antenna element is amplified and filtered before being combined using a power combiner. The output of the combiner serves as the input to the RF front-end.
4.1.2 Single-Stage Broadband Antenna

In this configuration, a single antenna element is designed to have a bandwidth wide enough to receive all the signals in the required frequency band. For example, the antenna element will have a bandwidth of 1.1 GHz to 1.6 GHz, which includes GPS L5/Galileo E5a at 1176.45 MHz, GPS L2 at 1127.60 MHz and GPS L1/Galileo E1 at 1575.42 MHz. This setup is shown in Figure 4-3.

**Figure 4-1: Single Frequency Antenna Subsystem**

**Figure 4-2: Multi-frequency Antenna Subsystem Using Multiple Antenna Elements**
The LNA is typically the first component after the antenna element. By choosing the first component of the system as a LNA with a low noise figure (typically 2-3 dB) and reasonable gain (typically 25 dB) the effect of any subsequent component in the system does not significantly impact the overall noise figure of the system \( F \), which can be deduced from the \textit{Eq 18}.

\[
F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_2 G_1} + \cdots + \frac{F_n - 1}{G_n \cdots G_2 G_1} \tag{24} \text{ Eq 18}
\]

where \( F_i \) and \( G_i \) (\( i=1,2 \ldots n \)) are noise figure and gain of the component in the cascaded RF chain \[24\].

Based on the application, a preselector, which is typically the first BPF after the antenna, is used to provide selectivity for the signals, help reject the image frequencies, and minimize the chance the amplifier will go into saturation (and produce spurious signals).

\textit{Figure 4-3: Multi-frequency Antenna Subsystem Using A Single Wideband Antenna Element}
4.1.3 Signal and Noise Power at the Input to the RF Front-end

The GPS L1 C/A code signal level at the input to the antenna element on the surface of the Earth is considered to be \(-130\) dBm. The noise floor at the antenna element, \(N\), is given by:

\[
N = 10\log_{10}(kTB) \text{ in dBW/Hz} \quad [24],
\]

where \(k\) is Boltzman’s constant, \(1.38e-23\) Joules/Kelvin, \(T\) is the temperature at the antenna, 290 Kelvin, and \(B\) is the bandwidth of the receiver in Hertz.

For a system where the 3 dB bandwidth is considered to be 16 MHz (i.e., GPS L1/Galileo E1), the noise floor can be computed as 
\[-114\text{ dBm/MHz} + 10\log_{10}(16) = -102\text{ dBm}.\]

Assuming that the overall gain provided by the antenna subsystem is 20 dB (i.e., LNA provides gain of 25 dB, BPF insertion loss of -1 dB and power combiner insertion loss of -4 dB) power level of the GPS L1 C/A signal is at -110 dBm (i.e., -130+25-1-4) and the noise floor is at -82 dBm (i.e., -102+20) at the output of the subsystem. Since the power level of the noise floor is higher (i.e., 28 dB higher for a 3 dB bandwidth of 16 MHz) than the power level of the signal, the power level of the noise floor is used as input to the RF front-end in order to compute the necessary amplification required for the ADC [24].

While the bandwidth of the antenna subsystem may change for various design approaches, which will in turn change the value of the noise power level, a nominal value of -85 dBm will be assumed and used for all four design approaches.
4.2 RF Front-end

The Direct RF sampling technique has been employed in the design of the RF front-end. This section describes in detail the four different approaches that were investigated which were broadly based on:

1. Civilian applications needing high accuracy (e.g. terrain mapping),
2. General aviation application with some signal limitations (e.g. L2 signal is not protected under the Aeronautical Radio Navigation Service (ARNS) band),
3. Size constraints with low power low cost premise (e.g. mobile devices), and
4. Three parallel channels to independently process each signal hence eliminating the concerns of inadvertent interference.

The primary components used in the four designs are identical and any changes or modifications are explained in that particular design section.

4.2.1 Design Approach I – L1, L2, L5 using Two ADCs

4.2.1.1 Salient Features of Design Approach I

This design approach accommodates most civilian/open service signals like GPS L1 C/A, GPS L1C, GPS L2C, GPS L5, Galileo E1 and Galileo E5a. It takes advantage of the fact that GPS L1 - Galileo E1 and GPS L5 – Galileo E5a are co-located in frequency.
Using the equations *Eq 14* to *Eq 16* defined in Section 3.3.2, the sampling frequency is carefully chosen for Channel 1 where multiple frequencies are down-converted using the same ADC.

The disadvantages with this approach are:

- Interference (e.g. jamming) on any one of the signals, either L1 (GPS L1/Galileo E1) or L2 (GPS L2) will cause adverse effects to both the sampled signals in that particular channel.
- Careful consideration is needed in the design of the digital IF filter at baseband processing to separate the L1 and L2 signals.

This approach could be used in high performance application where faster acquisition (time-to-first-fix) times are needed (pilot channel tracking) with high accuracy since it takes advantage of the longer codes on GPS L2C, faster chipping rate on GPS L5/Galileo E5a and interoperability of the signals GPS and Galileo signals.

4.2.1.2 Design Approach I – Description

Design Approach I is a dual-channel approach, based on Direct RF Sampling, which uses the bandpass sampling technique and is illustrated in *Figure 4-4*. 
In this design three frequencies, 1575.42 MHz containing the GPS L1/Galileo E1 over 16 MHz bandwidth, 1227.6 MHz containing GPS L2C over 10 MHz bandwidth and 1176.45 MHz GPS L5/Galileo E5a over 24 MHz bandwidth are considered.

It is assumed that an antenna subsystem with multiple antennas as shown in Figure 4-2 is used to receive signals mentioned above.

As depicted in Figure 4-4, after the initial stages of filtering and amplification, the signal is divided into two channels, with one channel dedicated to the GPS L1/Galileo E1 and GPS L2C frequencies and the second channel dedicated to the GPS L5/Galileo E5a signals. Each channel provides further filtering using BPFs as well as amplification before the signal is sampled at the ADC. Channel 1 provides two separate BPFs for the signals at L1 and L2 frequencies respectively.
Each of the signals is sampled using a common sampling frequency of 66.0625 MHz and down-converted to intermediate frequencies computed using the condition in Eq 15 as follows:

\[ \text{fix}\left(\frac{1575.42}{66.0625/2}\right) = \text{fix}(47.69) = 47. \]  
Since the result is an odd integer, IF is computed as

\[ \text{IF}_{L1/E1} = 66.0625 - \text{rem}(1575.42, 66.0625) = 10.080004 \text{ MHz}. \]  
Similarly the other IFs are also computed as \( \text{IF}_{L2} = 27.5875 \text{ MHz} \) and \( \text{IF}_{L5/E5a} = 12.675 \text{ MHz} \).

The bandpass sampling frequencies, \( F_{s1} \) and \( F_{s2} \), for ADCs on both Channels 1 and 2 is computed as 66.0625 MHz as shown in Figure 4-6 and based on the equations Eq 14 through Eq 16 described in Section 3.3.2 and the 3 dB bandwidth is specified by the BPF specification in Table 4-1.

The components of the front-end shown in Figure 4-4 are explained as follows:

**Triplexer:** The triplexer as shown in Figure 4-5 consists of three BPFs (i.e., BPF\(_{L1}\), BPF\(_{L2}\), BPF\(_{L5/E5a}\)) in parallel.
The output of the antenna is fed to the triplexer. The first step in the triplexer is the power splitter (e.g. Mini-Circuits 3-Way Power Splitter [25]). It divides the signal into three separate channels, which serve as an input to each of the BPFs. As three signal frequencies are considered, three BPFs that can filter each signal of interest in the bandwidth around its particular center frequency are used. The output of each BPF is then combined in a power combiner before being fed to the amplifier. The specifications of the BPFs are listed in Table 4-1.

During the design of the triplexer careful considerations for rejecting the image frequencies are taken i.e., for a given sampling frequency all the frequencies that can alias to the same IF as the signal of interest are to be rejected. For example the image frequencies to look out for GPS L1/Galileo E1, apart from other GPS/Galileo signals, are given in the Table 4-3.
Table 4-1: BPF Specifications for Design Approach I

<table>
<thead>
<tr>
<th>Package</th>
<th>Surface Mount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Ceramic Band Pass 4-pole 6 mm</td>
</tr>
<tr>
<td>BPF&lt;sub&gt;L1&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>FC</td>
<td>1575.42 MHz</td>
</tr>
<tr>
<td>Insertion Loss @ FC</td>
<td>&lt; 2.0 dB</td>
</tr>
<tr>
<td>3.0 dB pass band</td>
<td>16 MHz</td>
</tr>
<tr>
<td>Return Loss</td>
<td>&gt; 15 dB over the center 10 MHz of the BW</td>
</tr>
<tr>
<td>Rejection</td>
<td>&gt; -20 dBc @ F&lt;sub&gt;c&lt;/sub&gt; ± 30 MHz</td>
</tr>
<tr>
<td></td>
<td>&gt; -30 dBc min @ 1227.624 MHz</td>
</tr>
<tr>
<td>BPF&lt;sub&gt;L2&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>Fc</td>
<td>1227.6 MHz</td>
</tr>
<tr>
<td>Insertion Loss @ Fc</td>
<td>&lt; 2.0 dB</td>
</tr>
<tr>
<td>3.0 dB pass band</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Return Loss</td>
<td>&gt; 15 dB over the center 4 MHz of the BW</td>
</tr>
<tr>
<td>Rejection</td>
<td>&gt; -20 dBc @ F&lt;sub&gt;c&lt;/sub&gt; ± 30 MHz</td>
</tr>
<tr>
<td></td>
<td>&gt; -30 dBc min @ 1575.42 MHz</td>
</tr>
<tr>
<td>Package</td>
<td>2.97 x 1.0 x .53 inches SMD Leadless</td>
</tr>
<tr>
<td>BPF&lt;sub&gt;L5/E5a&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>FC</td>
<td>1176.45 MHz</td>
</tr>
<tr>
<td>Insertion Loss @ FC</td>
<td>&lt; 2.0 dB</td>
</tr>
<tr>
<td>3.0 dB pass band</td>
<td>24 MHz</td>
</tr>
<tr>
<td>Return Loss</td>
<td>&gt; 15 dB over the center 10 MHz of the BW</td>
</tr>
<tr>
<td>Rejection</td>
<td>&gt; -20 dBc @ F&lt;sub&gt;c&lt;/sub&gt; ± 30 MHz</td>
</tr>
<tr>
<td></td>
<td>&gt; -30 dBc min @ 1227.624 MHz</td>
</tr>
</tbody>
</table>

**Amplifiers:** The next stage in the front-end is the amplification. It consists of three cascaded amplifiers (e.g. Teledyne/Cougar Cascadable Amplifier [26]) each with a gain of 24 dB and a noise figure of about 2.3 dB. The amplifiers are connected in series providing an overall gain of about 72 dB. The cascaded amplifiers should provide high gain flatness in the region of operation and an input standing wave ratio (SWR) less than 2.0:1. The specifications for the amplifier used for cascading is listed in Table 4-2.
Table 4-2: Specifications of the Amplifier after the Triplexer for Design Approach I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (specified for 0 – 50 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain (dB)</td>
<td>24</td>
</tr>
<tr>
<td>Gain Flatness (dB)</td>
<td>±0.8</td>
</tr>
<tr>
<td>Standing Wave Ratio or SWR</td>
<td>Output – 1.7:1</td>
</tr>
<tr>
<td></td>
<td>Input – 1.9:1</td>
</tr>
<tr>
<td>Power output at 1 dB compression point (dBm)</td>
<td>14</td>
</tr>
</tbody>
</table>

*Power Splitter:* The current setup for the RF front-end is divided into two separate channels - one for GPS L1/Galileo E1, GPS L2 and the second for GPS L5/Galileo E5a. Hence the signal is divided into two channels using a 2-port power splitter (e.g. Mini-Circuits 2-Way Power Splitter [27]), with the assumption that both the ports are matched. A minimal 3 dB loss is assumed between the input and output with no phase changes.

*Variable Gain Amplifier:* This last stage of amplification occurs before the signal is fed to the ADC in each channel. The stage provides the amplification needed to bring the signal up to the power level required to activate all the levels of the ADC. Care is taken, since if too much amplification is provided the signal might saturate the ADC producing erroneous results. A series of wideband amplifiers or a variable gain amplifier with a reasonable amplifying range is used to cover GPS L1/Galileo E1 and GPS L2 bands. The goal is to raise the noise floor close to the maximum range of the ADC. The sampling frequency of the ADC in this approach is 66.0625 MHz (the choice for this frequency is discussed in the next section).
If we consider the maximum voltage needed to exercise at least 3 bits of the ADC as 400mV, this translates to \((0.4)^2 / (50) = 3.2 \text{ mW} \approx 5 \text{ dBm}\) [24], assuming a characteristic impedance of 50 ohms. Thus the noise floor should be amplified up to this power level hence needing a total gain of 90 dB (i.e., 5 – (-85), where -85 dBm is the power level of the noise at the output of antenna system) [24]. In the first cascaded stage a total 72 dB gain is already provided needing at least 18 dB of additional gain in the Variable Gain Amplifier stage not considering loss due to filter and power combiner/splitter.

Table 4-3: List of Image Frequencies for GPS L1/Galileo E1 in Design Approach I

<table>
<thead>
<tr>
<th>Image Frequency (MHz)</th>
<th>IF (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1133.2</td>
<td>10.088</td>
</tr>
<tr>
<td>1199.2</td>
<td>10.075</td>
</tr>
<tr>
<td>1397.4</td>
<td>10.088</td>
</tr>
<tr>
<td>1443.3</td>
<td>10.075</td>
</tr>
<tr>
<td>1463.5</td>
<td>10.075</td>
</tr>
<tr>
<td>1509.3</td>
<td>10.088</td>
</tr>
<tr>
<td>1661.7</td>
<td>10.088</td>
</tr>
<tr>
<td>1707.6</td>
<td>10.075</td>
</tr>
<tr>
<td>1727.7</td>
<td>10.075</td>
</tr>
<tr>
<td>1773.6</td>
<td>10.088</td>
</tr>
<tr>
<td>1925.9</td>
<td>10.088</td>
</tr>
<tr>
<td>1971.8</td>
<td>10.075</td>
</tr>
</tbody>
</table>

**Analog to Digital Convertor (ADC):** The ADC is the one of the most important components of the RF front-end design. The requirements of the ADC drive most of the design specifications of the RF front-end.
The ADC sampling frequency of 66.0625 MHz is generated based on using the Tyco/MA-COM Phase Locked Loop (PLL) based frequency synthesizer [28] as seen in Figure 4-6.

![PLL Synthesizer @ 924.875MHz](image)

\[ F_s = \frac{F_{PLL}}{14} \]

\( F_s = 66.0625 \text{MHz} \)

*Figure 4-6: ADC Clock or Sampling Frequency Generation for Design Approach I*

This particular component has built into it a Temperature Controlled Crystal Oscillator (TCXO), along with Voltage Controlled Oscillator (VCO), phase comparator and a loop filter. The synthesizer has a frequency range of 900 - 950 MHz with a center frequency of approximately 924.875 MHz. A single frequency divider of value 14 is used at the output of the PLL to generate Fs1 and Fs2 at 66.0625 MHz.

The ADC sampling frequency used for the L1/L2 and L5/E5a channels is computed to be the same to reduce the burden of generating another sampling frequency and hence reduce the complexity of the circuit.

The sampling frequency of 66.0625 MHz for the L1/L2 channel is computed taking into consideration both the center frequency and also the bandwidth of the signal being sampled (3 dB bandwidth). The list of signals in Table 4-3 are the computed image
frequencies based on the sampling frequency of 66.0625 MHz and the corresponding IF they will alias to [15] [20]. None of these listed frequencies are considered a serious threat hence validating the choice of the sampling frequency for GPS L1/Galileo E1.

4.2.2 Design Approach II – L1, L5 with Two ADCs

4.2.2.1 Salient Features of Design Approach II

This design approach accommodates most civilian/open service signals like GPS L1 C/A, GPS L1C, GPS L5, Galileo E1 and Galileo E5a. As in the previous approach, advantage is taken of the fact that GPS L1 - Galileo E1 and GPS L5 – Galileo E5a are co-located in frequency. GPS L2C signal, which is not in the Aeronautical Radio Navigation Service (ARNS) protected band, is not used by the Original Equipment Manufacturers (OEM) in their designs for airborne receivers. Hence this approach, which does not include the GPS L2C signal, can be used in aviation applications.

4.2.2.2 Design Approach II – Description

This approach is based on the Design Approach I with the exception being that the GPS L2 frequency is not taken into consideration. This reduces the complexity of the baseband processor.
The note worthy changes in the architecture of the design is as follows:

**Diplexer:** Since only two signals for processing are considered, the triplexer is replaced with a diplexer with two components only the BPF\(_{L1}\) and BPF\(_{L5/E5a}\). The specifications of the BPFs remain the same as in Design Approach I. The power splitter splits the incoming signal into two channels and the power combiner combines two input signals and sends it out the wideband amplifier section.

![Diagram of RF Front-End based on Design Approach - II](image)

*Figure 4-7: RF Front-End based on Design Approach - II*

All the GPS L2 related components are removed from channel 1 hence reducing the number of components. All other components in the design essentially remain the same as in Design Approach I.
4.2.3 Design Approach III – L1, L2, L5 with One ADC

4.2.3.1 Salient features of Design Approach III

Similar to Design Approaches I and II, this design approach also accommodates most civilian/open service signals like GPS L1 C/A, GPS L1C, GPS L2C, GPS L5, Galileo E1, and Galileo E5a and takes the advantage of the fact that GPS L1 - Galileo E1 and GPS L5 – Galileo E5a are co-located in frequency. Using the equations Eq 14 to Eq 17 defined in Section 3.3.2, the sampling frequency is carefully chosen for the single channel since all signals under consideration are down-converted using the same ADC. There is a further reduction in the parts count and hence size of the receiver, as there is only one channel with a single ADC, hence making it desirable for the RF front-ends of a Personal Navigation Device (PND).

This design approach shares its disadvantages with Design Approach I which are:

- Any interference on one of the signals either L1 (GPS L1/Galileo E1) or L2 (GPS L2) or L5 (GPS L5/Galileo E5a) will cause adverse effects on the sampled data. Hence the BPFs need to be carefully designed.

- The digital filter at the baseband processor level needs to be carefully designed to separate the desired signals for processing.
Since the sampling frequency of the ADC is higher than that required in the previous two design approaches, it adds additional computational burden at the baseband processor but reduces the power constraints as only a single ADC is employed.

4.2.3.2 Design Approach III – Description

This design is significantly different from the other two approaches as illustrated in Figure 4-8. The difference lies in the processing of the data after the first stage of amplification. The output of the amplifier is split into three paths and fed to three individual BPFs. The output of each BPF is now combined in a power combiner and input to a single ADC.

In this approach all the signals are sampled using a single ADC which is clocked at a frequency of 113.25 MHz as computed using the equations Eq 14 to Eq 17 from Section 3.3.2 to accommodate all the three frequency bands. As the sampling frequency is directly related to signal bandwidth (or in this case 3 dB bandwidth), to keep the

**Figure 4-8: RF Front-End Design Approach III**
sampling frequency small, the 3 dB bandwidth of the BPFs is lowered. The bandwidths are chosen to accommodate at least the main lobe of the signal spectrum. Thus the effective bandwidth of L1 band is now reduced to 12 MHz from its previous value of 16 MHz, for L2 band is reduced to 2.8 MHz from 10 MHz and for L5 band is reduced to 20 MHz from 24 MHz. The new sampling frequency generation is shown in Figure 4-9. Hence based on the new sampling frequency of 113.25 MHz, the IF is computed using the Eq 15 as follows:

\[
\text{fix}\left(\frac{1575.42}{113.25/2}\right) = \text{fix}(27.82) = 27. \text{ Since the result is an odd integer, IF is computed as }
\]

\[
\text{IF}_{L1/E1} = 113.25 - \text{rem}(1575.42, 113.25) = 10.799 \text{ MHz. Similarly other IFs are computed as IF}_{L2} = 18.150 \text{ MHz and IF}_{L5/E5a} = 43.95 \text{ MHz.}
\]

---

**Figure 4-9:** ADC Clock or Sampling Frequency Generation for Design Approach III
4.2.4 Design Approach IV – L1, L2, L5 using Three ADCs

4.2.4.1 Salient features of Design Approach IV

Three independent channels are used here for sampling the three bands. The constraints on the bandwidth are less as a separate ADC is used to sample each band. The sampling frequency of the ADC Fs1/Fs2/Fs3 remains at 66.0625 MHz.

This design can be utilized in research applications where wide pre-correlation bandwidths are a requirement along with the ability to process each band independently. It can also be utilized for high performance applications in the military or for surveying in Geographic Information Systems (GIS).

4.2.4.2 Design Approach IV – Description

This approach is an extension to Design Approach II, wherein another independent channel is added for GPS L2 frequency, as illustrated in *Figure 4-10*. All other components of the design approach remain the same.
**Figure 4-10:** RF Front-End based on Design Approach IV
4.2.5 Summary of Design Approaches

The key features of all four design approaches are summarized in Table 4-4.

Table 4-4: Summary of Design Approaches

<table>
<thead>
<tr>
<th>Design Approach</th>
<th>Signal Considered</th>
<th>3 dB Bandwidth (MHz)</th>
<th>Intermediate Frequency (MHz)</th>
<th>Number of Channels</th>
<th>ADC Sampling Frequency (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GPS</td>
<td>Galileo</td>
<td>L1</td>
<td>L2</td>
<td>L5</td>
</tr>
<tr>
<td>I</td>
<td></td>
<td></td>
<td>L1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td></td>
<td></td>
<td>L1</td>
<td>L5</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td></td>
<td></td>
<td>L1</td>
<td>L2</td>
<td>L5</td>
</tr>
<tr>
<td>IV</td>
<td></td>
<td></td>
<td>L1</td>
<td>L2</td>
<td>L5</td>
</tr>
</tbody>
</table>

These design approaches have been evaluated using Ansoft Designer® in the next chapter.
5 RF FRONT-END SIMULATION USING ANSOFT DESIGNER® AND RESULTS

The design approaches mentioned in the previous section can be tested two different ways. The first method is to physically implement the design on a printed circuit board using real components.

The disadvantages of this method are:

- Once built, the performance of the system cannot be adjusted without physically changing the components.
- The BPF components for each of the approaches need to be custom built due to their distinct specifications, rendering this method costly.

The second method is to simulate the components of each design approach. The software tool used here was Ansoft Designer®. Ansoft Designer® is a leading industry software which provides an environment for simulation and modeling of a system level design containing analog/RF components with fully integrated tools for verification and optimization. The advantages of using Ansoft Designer® are:

- The performance of the system components from the in-built library is comparable to that of real components.
- It provides an opportunity to adjust the various component level specifications for optimum performance before implementing the design physically.
- It also allows for comparison of performance of each of the design approaches.
It allows for a seamless integration with other Ansoft software modules like Nexxim® and HFSS®.

System level analysis of the design approaches can be done both in frequency domain and in time domain. The following sections elaborate on:

- Frequency domain analysis to show the behavior of system in the following terms when the system input frequency is swept from 1 GHz to 2 GHz to measure the performance of the amplifiers and the filters in the system in the frequency band of interest:
  - forward gain – the overall gain through the system from an input to output,
  - return loss – defined as the ratio of reflected power to input power,
  - group delay – the delay variation for a modulated signal to pass through a band limiting component (i.e., the derivative of the phase with respect to frequency) [29],
  - noise figure – overall noise added to the system,
  - third-order intercept point (IP3) – is a measure of the third-order intermodulation products generated when two signals arrive simultaneously at the input of a device (e.g. amplifier) [30], and
  - 1 dB compression point (P1dB) – is the input signal power for which the output of a component is 1 dB less than the desired linear output [30].

- Time domain analysis to show that the selected sampling frequency in fact shall produce the IF as computed in the previous sections.
To create a signal in the time domain that truly represents a signal at RF over a given period of time, according to the Nyquist Sampling theorem, the sampling frequency needed to be at least twice of the highest frequency component of the input. Hence, to create a sine wave at a frequency $f_C$ MHz, the minimum sampling frequency needed is greater than $2f_C$. For a true representation, the sampling frequency, in reality, needs to be much higher than $2f_C$. When this criterion is applied, the number of samples generated imposed a memory restriction in Ansoft Designer® in this specific case causing the simulation to terminate. On the other hand, if the minimum condition is used to create the signal, the results are erroneous as the input signal is not accurately represented. In order to overcome this hurdle, an input signal of shorter duration but with a higher sampling rate was created.

5.1 Design Approach I in Ansoft Designer

The design approach components defined in the Figure 5-1 is a combination of both in-built components from the library of Ansoft Designer® and in-built components with certain properties modified per real component specifications. For example, the splitters (i.e., 3-way and 2-way) used in this design are Ansoft in-built components, while the BPF, amplifier components are in-built components modified per specs of real components.
5.1.1 Frequency Domain Analysis of Design Approach I

The frequency domain analysis setup used to evaluate the Design Approach I is illustrated in Figure 5-1. In Figure 5-1, PNUM=1 represents the input port where the RF input signal of 1 GHz to 2 GHz at -85 dBm is provided to the system. PNUM=2 and PNUM=3 are the output ports at which resultant plots of the system minus the ADC are created. The plots generated at the output ports mentioned above characterize the return loss, forward gain and group delay. These plots are used to evaluate the performance of the system in the frequency bands of interest (L1, L2 and L5).

The results for the frequency domain analysis of Design Approach I are:

- The result plot for the return loss and system gain from input port PNUM=1 to the output ports PNUM=2 and port PNUM=3 is shown in the Figure 5-2.
- From the result plot, the system gain S21 and S31 of the system at the frequencies of interest not only shows that the frequencies in the band of interest are adequately amplifier but also shows that the signals outside the band of interest are well mitigated.
- For this simulation of Design Approach I, the power combiner being the first component, the return loss results indicate that the return loss for the entire system are very low (i.e., poor). The low value of return loss is not an indication of performance of the system as much as it is the characteristic of the power combiner/splitter in combination with the triplexer that follows it (the return loss
of just the power combiner is very high (i.e., good)). Additional performance plots are included in Appendix B.

- The plot with group delay at both the output ports is shown in Figure 5-3. As defined earlier the group delay measures the derivative of the signal phase with respect to frequency in the RF chain which in turn is a measure of the possible performance degradation of the system.

- It should also be noted that the group delay is different across the three frequencies. In order to take advantage of the multiple frequencies in the receiver and correct for the ionospheric delays across two or three frequencies the group delay should be constant across all three frequencies. Hence this difference in value of the group delay should be accounted for in the baseband processing.

- The Figure 5-3 also shows that the group delay is not constant in the signal bandwidth of interest which can be attributed to the high Q of the filters in the system. This group delay variation will degrade the signal and should be minimized. A closer look at this variation is illustrated in Appendix B.

- Budget analysis was performed at certain frequency (i.e., L1, L2 and L5) in Ansoft Designer® on this design approach with overall system noise figure, overall forward gain, output power at IP3 and P1dB, and total output power of the system as outputs for the analysis.

- The overall system noise figure was relatively high and this can be attributed to the three passive components of the system which here are a power splitter, filter and power combiner as these are the component after the antenna system defined
in Section 4.1. This relatively high value is not a concern since the overall system noise figure will be dominated by the noise figure and gain of the LNA used in the active antenna depicted in *Figure 4-1* through *Figure 4-3*.

- Additional amplification should be provided at the variable gain amplifier stage, based on the value of total output power of the system at the output ports, to bring the output power level up to the level required by the ADC (i.e., 5 dBm).
Figure 5-1: Design Approach I in Ansoft Designer®
Figure 5-2: Return Loss S11 [dB] and Forward Gain S21 [dB] & S31 [dB] for Design Approach I
Figure 5-3: Group Delay, GD21 [ns] & GD31 [ns], for Design Approach I
5.1.2 Design Approach I using ‘N-Port’

‘N-Port’ is an in-built component in the Ansoft Designer® component library which lets the user change the specifications of the N-Port device by entering a formatted definition file with the scattering (S) parameters defined for the N ports of the component. In this simulation, data (insertion loss, return loss, etc.) from the specification sheets for Mini-Circuits 2-way [27] and 3-way splitters [25] were used to compute the S parameters in Matlab®. These files created using Matlab® were used to define the specifications of the N-Port component to create a 3-port (2-way splitter) and a 4-port (3-way splitter) device. This was an exercise where the in-built component performance was tested versus a realistic component. The frequency domain setup for Design Approach I using N-Ports is shown in Figure 5-4. The corresponding results of this approach are observed in Figure 5-5 (return loss and forward gain) and Figure 5-6 (group delay) respectively.
Figure 5-4: Design Approach I designed using an 'N-port' to replace 3-Way and 2-Way Power Splitters/Combiners
Figure 5-5: Return Loss, S11 [dB] and Forward Gain, S21 & S31 [dB] for Design Approach I designed using 'N-Port'
Comparing the two figures generated for Design Approach I, Figure 5-2 and Figure 5-3 with Figure 5-5 and Figure 5-6 respectively, the variation in the return loss for each of the two systems is in the range of -2 dB and -5 dB respectively. As the variation in return loss in both systems is comparable, it is assumed that the use of the N port in the design provides results that are acceptable. This is the premise for the following design approaches in Ansoft Designer®.
The splitter BPF combination which forms the triplexer also performs similar to the original setup. This is inferred by comparing Figure 5-3 and Figure 5-6 that depict similar group delays for the two topologies.

5.1.3 Time domain Analysis

For performing the time domain analysis the setup in Figure 5-7 was used instead of extending the existing setup used for the frequency domain analysis as the computational burden on Ansoft for this application was far too great and the simulation does not complete to produce any significant results.

The setup in the Figure 5-7 includes a signal generator that generates a signal containing ‘NS’ samples at sampling rate ‘SR’ hence producing a signal NS/SR seconds long in time. The sampling rate SR should be chosen based on Nyquist criteria, such that the SR should be greater than twice the highest frequency component. Hence SR is chosen as 4*1580 MHz for all frequencies.

To keep the ADC in this setup simple, only 3 bits per sample are considered with a maximum input range of 400mV peak-to-peak. The bandpass sampling frequency used here for sampling the input signal was set using a digital clock which is clocked at 66.0625 MHz. The component ‘RFILESRC’ takes C/A code generated in Matlab® as input.
Simulation for Channel 1 (L1/L2):

By multiplying the C/A code with the sine wave at the GPS L1 and GPS L2 frequencies of 1575.42 MHz and 1227.60 MHz respectively with an amplitude high enough to activate all 3 bits of the ADC, the input was generated by combining the two signals and is shown in Figure 5-8.

- The output of the ADC should show a spike at 10.1 MHz and 27.6 MHz for the bandpass sampled L1 and L2 signals respectively, but that is not the case.

- Hence it is observed that for lack of high enough sampling rates the input signal could not be bandpass sampled.
Figure 5-7: Time-Domain Analysis Setup for Design Approach I - Channel 1 (L1/L2)
Figure 5-8: Signal Input to the Channel 1 (L1/L2) Time-Domain Analysis Setup.
5.2 Design Approach II in Ansoft Designer®

In the simulation of the different design approaches, the same numbers of amplifiers were used per channel to show the variation in gain pattern across the design approaches based on if a triplexer or a diplexer was used and also in quantity (more than one triplexer in a design). The two-channel Design Approach II is illustrated in Figure 5-9.

The setup for the frequency-domain analysis remains common across all the design approaches. The two major differences in the results compared to Design Approach I are the amount of gain that is achieved, which is slightly higher in the given band of interest, which in this case, are L1 and L5 bands. Also the return loss is slightly better as seen in Figure 5-10 since the 2-way splitter replaces the 3-way splitter from Design Approach I. The group delay is unaffected as the filter constraints remained the same as Design Approach I as seen in Figure 5-11. Once again the group delay differences at the L1 and L5 frequencies would need to be included in the baseband processing and the impact of the in-band group delay ripple would need to be considered in the baseband processing as well.
Figure 5-9: Design Approach II in Ansoft Designer®
Figure 5-10: Return Loss, S11 [dB] and Forward Gain, S21 & S31 [dB] for Design Approach II
Figure 5-11: Group delay, GD21 & GD31 [ns], for Design Approach II
5.3 Design Approach III in Ansoft Designer®

This design approach as illustrated in Figure 5-12 can be deemed the most complicated design of all the afore mentioned design approaches because of the bandwidth restrictions imposed to keep the sampling frequency low. Hence there is a change in the 3 dB bandwidths of the BPFs and also the order of the filters. The BPF parameters are set as follows:

- For L1 the new bandwidth is 12 MHz (previously 16 MHz), but the order of the filter is still at 4.
- For L2 the new bandwidth is 2.8 MHz (previously 10 MHz) and order of the filter is reduced to 3, which will decrease the performance rejection for a given size of the filter.
- For L5 the new bandwidth is 20 MHz (previously 24 MHz) and the order of the filter is still at 4.

As the number of splitters increase a significant reduction in gain of the system is observed as shown in Figure 5-14. Changes in the filter parameters did not adversely affect the group delay as seen from Figure 5-13.
Figure 5-12: Design Approach III in Ansoft Designer®
Figure 5-13: Group delay, GD21 [ns], for Design Approach III
5.4 Design Approach IV in Ansoft Designer®

This approach as illustrated in Figure 5-15 is an extension of the Design Approach II or can also be considered as an alternate to Design Approach I, where instead of using a single channel for both L1 and L2 frequencies two independent channels are considered. Hence the results as seen in Figure 5-17 for return loss is similar to Figure 5-2 for Design Approach I. Group delay results are also similar as observed from Figure 5-16 and Figure 5-3.
Figure 5-15: Design Approach IV in Ansoft Designer®
Figure 5-16: Group delay, GD21, GD31 & GD41 [ns], for Design Approach IV
Figure 5-17: Return Loss, S11 [dB] and Forward Gain, S21, S31 & S41 [dB] for Design Approach IV
6 RESULTS AND DISCUSSIONS

6.1 Analysis of the Four Design Approaches

An analysis of the four design approaches is presented with respect to the advantage and disadvantages offered by each of them.

6.1.1 Design Approach I – L1, L2, L5 using Two ADCs

The highlight of Design Approach I is being able to handle all the civilian signals that are being transmitted in the GPS and Galileo spectra with two ADCs. This was done to utilize the maximum extent of each of the civil signals with moderate component power consumption.

The advantage of this system is:

- There are two channels for processing the three signals under consideration. This reduces the parts count and makes it a more cost effective implementation with lower power consumption as compared to Design Approach IV.

The disadvantages of this system are:
○ A single ADC is used to sample both the L1 and L2 signals in channel 1. Interference on either of these signals will cause degradation in the other signal as well. This could also lead to the saturation of the ADC.

○ The difference in group delay across the different frequencies needs to be additionally compensated for at the baseband processing level when multi-frequency ionospheric delay corrections are performed.

○ As compared to the Design Approach II, an increased number of splitters/combiners are used; the amplification needed is greater to compensate for the loss per channel that the splitters/combiners incorporate.

6.1.2 Design Approach II – L1, L5 with Two ADCs

The prominent feature of this approach is the absence of the processing of the L2 signal that differentiates it from Design Approach I. Each signal has its own dedicated ADC for sampling.

The advantages of this system are:

○ There is no concern regarding inadvertent interference that could be produced since there is only one signal being processed per channel.

○ Also, the signals being considered here lie in the ARNS band making this approach conducive to avionics applications.
Due to the fact that only two signals are being processed, compared to Design Approach I, the complexity of channel 1 in the system is reduced due to a reduced number of components. (For e.g. a diplexer versus a triplexer and a 2-way splitter versus a 3-way splitter).

The disadvantage of this system is:

- There is an opportunity loss of higher accuracy due to the absence of the L2 signal in the computation of the PVT solution, but this highly dependent on application.

6.1.3 Design Approach III – L1, L2, L5 using One ADC

A single ADC is used to sample all the signals under consideration. This significantly increases the sampling frequency of the ADC as well as the 3 dB bandwidth constraints of the filters to accommodate the three signals.

The advantage of this system is:

- Greatly reduced parts count that leads to a smaller size of the RF front-end with lower power consumption as compared to Design Approaches I & II.
The disadvantages of this system are:

- The complexity in the design of the filters is significant as the constraints on the 3 dB bandwidth are higher.
- Interference on one signal introduces degradation on the other signals as well.
- Increased sampling rate of the ADC imposed additional requirements on its selection and baseband processing.

6.1.4 Design Approach IV - L1, L2, L5 using Three ADCs

This approach deals with the short coming of Design Approach II by adding another channel to process the L2 signal.

The advantage of this system is:

- There is no concern regarding inadvertent interference that could be produced since there is only one signal being processed per channel.

The disadvantage of this system is:

- Increase in parts count leads to a larger size of the RF front end with increased power consumption.
6.2 Suitability of Ansoft Designer® for Simulation

Once the frequency plan for each approach had been defined, it was necessary to verify its accuracy. Ansoft Designer® was chosen to implement the frequency plan for each of the four design approaches as it not only provided a low cost option compared to an actual physical implementation (printed circuit board) but it also is a great simulation environment with many advantages.

The advantages offered by Ansoft Designer® are:

- It has an extensive library of in-built components that can be used to implement the design.
- The specification of each component can be modified to provide optimum results.
- The impact of each component addition on the system performance can be easily studied.
- It also provides in-built tools for optimization of key parameters and to study their impact on the system performance.

The few disadvantages of Ansoft Designer® were:

- It was difficult to analyze the system with an input at RF in the time domain due to memory constraints particular to this application.
- Limited help documentation and support for errors encountered while performing system analysis with this license version.
CONCLUSIONS AND FUTURE WORK

The primary focus of this research has been to investigate design approaches for a GNSS receiver RF front-end based on direct RF sampling technique which would incorporate multiple GPS/Galileo civilian/open service signals taking advantage of the GNSS software design approach. Four design approaches were investigated based on four different applications and since all four design approaches discussed are application driven, hence they each have great potential for their particular application.

Using Ansoft Designer®, the four different approaches were simulated and the performance analyzed to investigate and verify the merit of each design approach based on the frequency domain and time domain analysis. The four design approaches were summarized with the advantages and disadvantages of each system documented.

The recommendations for future work are as follows:

- Physical implementation of all design approaches using off-the-shelf components.
- The main cost-driving factor in these approaches is the Bandpass Filter. This can be remedied by designing the filters using micro-stripline or stripline filters or a basic LC filter using Ansoft Designer® rather than custom designing a filter to be manufactured by a vendor.
o A trade study should be performed for the selection of ADC based on number of bits utilized, power consumption and cost to determine a more cost effective method of implementing the design approaches.

o The baseband processing for each approach can be simulated using Matlab® and Simulink®. This will allow for a cost effective method to be used for testing the design of the GNSS receiver front-end.
REFERENCES


APPENDIX A: MATLAB CODE

1. For Generation of Input Signal and CA Code for Time-Domain Analysis Setup

```matlab
% Signal Input for Ansoft Simulation
% Raghunath Viswanatha
% 9 January 2006,
% Edited 24 Feb 2006

clear all
close all
clc
tic
format compact
format short g

% Inputs
% Fc = [1575.42e6 1227.60e6 1176.45e6]; %Hz
% Fc = 1176.45e6;
Fc = input('Enter F_C value = ');
N = 4;
t_end = 0.9999999e-3; %Total time period 1ms
% Fs1 = 6.99953139e9; % Sampling Freq (Hz)
Fs1 = Fc(1)*N;
t = 0:1/Fs1:t_end; %Time Vector
% V_in = 2.25e-6; % volts ~ -100dBm
% V_in = 71e-9; % volts ~ -130dBm
% V_in = 3.16e-10; % volts ~ -160dBm
V_in = 0.225; % volts ~ 0dBm
prn=24;

% Generating the C/A Code for L1,L2
[CA,G1,G2] = prncode(prn);

% %Generating the I and Q code for L5
% [CA_I,CA_Q]=prncode_L5(prn);

clear G1 G2
% Upsampling the code accordingly as the sampling frequency
% L1L2code1 = upsample_updated(CA,Fs1,t_end);
L5code_I= upsample_updated(CA_I,Fs1,t_end);
% L5code_Q= upsample_updated(CA_Q,Fs1,t_end);

pack;
% clear Mcode1 L5code1
clear CA CA_I CA_Q
save Signal_IN_Ansoft.mat

% samples=2^18-270; %The entire sample space is not used
samples = length(t);
% L1 Signal Generation
Signal_1 = V_in*cos(2*pi*Fc(1)*t); % + 0.05*randn(size(t));
% Signal Modulation
Signal_MOD1 = L1L2code1 .* Signal_1;
% Signal_MOD1 = Signal_MOD1(1:samples);
% save Signal_MOD_L1.mat Signal_MOD1 -ascii -double
save Signal_MOD_L1.mat Signal.MOD1

clear Signal_1
```

FFT_Signal_MOD1 = fft(Signal_MOD1(1:samples));
N = Fs1/Fc(1);
c1 = (samples-1)*Fc(1)/Fs1;
n1 = -c1*N/2:1:c1*N/2;
fn1 = n1*Fc(1)/c1;  %Frequency Range

% Normalizing Output
 cn1 = 1/(N*c1) * FFT_Signal_MOD1;
cn1=fftshift(cn1)';
figure
plot(fn1,abs(cn1),'g')
grid on
% axis([1.5735e9 1.5775e9 0 1e-8]);
title('L1 - Magnitude Spectrum'),xlabel('Frequency --->Hz'),
% Clear some unused variables
 clear Signal_MOD1 FFT_Signal_MOD1 c1 n1 fn1 cn1

% L2 Signal Generation
% Signal_2 = V_in*cos(2*pi*Fc(2)*t);
% % L2 Signal Modulation
% Signal_MOD2 = L1L2code1 .* Signal_2;
% save Signal_MOD_L2.mat Signal_MOD2((samples) -ascii -double
% clear Signal_2
% FFT_Signal_MOD2 = fft(Signal_MOD2(1:samples));
% c2 = (samples-1)*Fc(2)/Fs1;
% N = Fs1/Fc(2);
% n2 = -c2*N/2:1:c2*N/2;
% fn2 = n2*Fc(2)/c2;  %Frequency Range
% %
% % cn2 = 1/(N*c2) * FFT_Signal_MOD2;
% cn2=fftshift(cn2)';
% %
% % figure
% % plot(fn2,abs(cn2),'g')
% % grid on
% % axis([1.225e9 1.230e9 0 1e-8])
% % title('L2 - Magnitude Spectrum'),xlabel('Frequency --->Hz'),
% %
% % clear Signal_MOD2 FFT_Signal_MOD2 c2 n2 fn2 cn2 L1L2code1
% %
% % L5 Signal Generation
% % Signal_3 = V_in*cos(2*pi*Fc(3)*t);
% % % L5 Signal Modulation
% % Signal_MOD3 = (V_in/sqrt(2)) *((L5code_I .* cos(2*pi*Fc(3)*t + pi/4)) + (L5code_Q .* sin(2*pi*Fc(3)*t + pi/4)));
% % figure,plot(Signal_MOD3(1:100000)),title('QPSK Mod')
% % save Signal_MOD_L5.mat Signal_MOD3(samples) -ascii -double
% clear Signal_3
% %
% % FFT_Signal_MOD3 = fft(Signal_MOD3(1:samples));
% % c3 = (samples-1)*Fc(3)/Fs1;
% % N = Fs1/Fc(3);
% % n3 = -c3*N/2:1:c3*N/2;
% % fn3 = n3*Fc(3)/c3;  %Frequency Range
% %
% cn3 = 1/(N*c3) * FFT_Signal_MOD3;
% cn3=fftshift(cn3)';
%
% figure
% plot(fn3,abs(cn3),’g’)
% grid on
% % axis([1.150e9 1.20e9 0 1e-8])
% title(’L5 - Magnitude Spectrum’),xlabel(’Frequency --->Hz’),
%
% clear Signal_MOD3 FFT_Signal_MOD3 c3 n3 fn3 cn3
Toc
II. Computation of Bandpass Sampling Frequency

% function [L_IF_FS] = bps(B1,B2)
% Raghunath V
% Bandpass Sampling (as suggested by Akos D.M.)
% Doctoral Thesis, Fritz J. Dolores H. Russ college of Engineering and Technology , Ohio University, August 1997

% Finding the right Sampling Frequency
% Nov 14, 2005
clear all
% clc

% % Signal two
fc1 = 1575.42;
fc2 = 1227.60;
fc3 = 1176.45;

B1 = 12;
B2 = 2.8;
B3 = 20;

% fs=66:0.0001:67;
fs = 30:0.01:120;
% fs=32.35714286;
% fs = 113.25;
fs1=fs;
fs2=fs;
fs3=fs;

% format long g
count=1;
index=1;
d=length(fs1);
h=waitbar(0,'Please Wait ...');
for i=1:d
if mod(fix(fc1/(fs1(i)/2)),2)==0,
if1(i)=rem(fc1,fs1(i));
else
if1(i)=fs1(i) - rem(fc1,fs1(i));
end

if mod(fix(fc2/(fs2(i)/2)),2)==0,
if2(i)=rem(fc2,fs2(i));
else
if2(i)=fs2(i) - rem(fc2,fs2(i));
end

if mod(fix(fc3/(fs3(i)/2)),2)==0,
if3(i)=rem(fc3,fs3(i));
else
if3(i)=fs3(i) - rem(fc3,fs3(i));
end

if ((if1(i)<((fs1(i)-B1)/2)) & (if1(i)>(B1/2))) & ((if2(i)<((fs2(i)-B2)/2)) & (if2(i)>(B2/2)) & (if3(i)<((fs3(i)-B3)/2)) & (if3(i)>(B3/2))) & (abs(if1(i)-if2(i))>(B1+B2)/2) & (abs(if1(i)-if3(i))>(B1+B3)/2) & (abs(if2(i)-if3(i))>(B2+B3)/2)
%%
F_if1(index)=if1(i);
F_if2(index)=if2(i);
F_if3(index)=if3(i);
F_fs(index)=fs(i);
index=index+1;
end
waitbar(i/d,h);
end
close(h);
%% FOR A SINGLE SAMPLING FREQ FOR MORE THAN ONE SIGNAL
L_IF_FS(1,:) = F_fs;
L_IF_FS(2,:) = F_if1;
L_IF_FS(3,:) = F_if2;
L_IF_FS(4,:) = F_if3;
%% FOR MULTIPLE FREQUENCIES WITH MULTIPLE SAMPLING FREQUENCIES
% L1 = F_fs1;
% L1(2,:) = F_if1;
% L1(2,:) = F_if1 -12;
% L1(3,:) = F_if1 +12;
%
% L5 = F_fs3;
% L5(2,:) = F_if3;

% plot(fs,(fs-B2)/2,’r’)
% hold on
% plot(fs,(fs-B1)/2,’g’)
% hold on
% plot(fs,B1/2,’g’);
% hold on
% plot(fs,B2/2,’r’);
% hold on
% plot(fs,if1,’.’
% hold on
% plot(fs,if2)
% ANS_fs1=sprintf(‘%f -> %f
’,F_fs1,F_if1);
% ANS_fs2=sprintf(‘%f -> %f
’,F_fs2,F_if2);
% disp(ANS_fs1)
% disp(ANS_fs2)
%% FOR WRITING TO A FILE
% L2_Band_fs = min(F_fs1)
% L2_Band_if = F_if1(find(min(F_fs1)))
%
% L1_Band_fs = min(F_fs2)
% L1_Band_if = F_if2(find(min(F_fs2)))
%
filename = strcat([\'L1-L2-L5 (\' num2str(B1) \' MHz-\' num2str(B2) \' MHz-\' num2str(B3) \' MHz) BPS Freq.txt\']);
fid1 = fopen(filename,\'w\');
for i=1:length(L_IF_FS(1,:))
fprintf(fid1,'\%f \%f \%f\n',L_IF_FS(1,i),L_IF_FS(2,i),L_IF_FS(3,i),L_IF_FS(4,i));
end
fclose(fid1);
%
plot(L1(1,:),L1(2,:),'g.'), hold on, plot(L1(1,:),L1(3,:),'g.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L2(1,:),L2(2,:),'r.'), hold on, plot(L2(1,:),L2(3,:),'r.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L3(1,:),L3(2,:),'b.'), hold on, plot(L3(1,:),L3(3,:),'b.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L4(1,:),L4(2,:),'c.'), hold on, plot(L4(1,:),L4(3,:),'c.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L5(1,:),L5(2,:),'m.'), hold on, plot(L5(1,:),L5(3,:),'m.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L6(1,:),L6(2,:),'y.'), hold on, plot(L6(1,:),L6(3,:),'y.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L7(1,:),L7(2,:),'k.'), hold on, plot(L7(1,:),L7(3,:),'k.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L8(1,:),L8(2,:),'w.'), hold on, plot(L8(1,:),L8(3,:),'w.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L9(1,:),L9(2,:),'g.'), hold on, plot(L9(1,:),L9(3,:),'g.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L10(1,:),L10(2,:),'r.'), hold on, plot(L10(1,:),L10(3,:),'r.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L11(1,:),L11(2,:),'b.'), hold on, plot(L11(1,:),L11(3,:),'b.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L12(1,:),L12(2,:),'c.'), hold on, plot(L12(1,:),L12(3,:),'c.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L13(1,:),L13(2,:),'m.'), hold on, plot(L13(1,:),L13(3,:),'m.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L14(1,:),L14(2,:),'y.'), hold on, plot(L14(1,:),L14(3,:),'y.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L15(1,:),L15(2,:),'k.'), hold on, plot(L15(1,:),L15(3,:),'k.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L16(1,:),L16(2,:),'w.'), hold on, plot(L16(1,:),L16(3,:),'w.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L17(1,:),L17(2,:),'g.'), hold on, plot(L17(1,:),L17(3,:),'g.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L18(1,:),L18(2,:),'r.'), hold on, plot(L18(1,:),L18(3,:),'r.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L19(1,:),L19(2,:),'b.'), hold on, plot(L19(1,:),L19(3,:),'b.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L20(1,:),L20(2,:),'c.'), hold on, plot(L20(1,:),L20(3,:),'c.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L21(1,:),L21(2,:),'m.'), hold on, plot(L21(1,:),L21(3,:),'m.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L22(1,:),L22(2,:),'y.'), hold on, plot(L22(1,:),L22(3,:),'y.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L23(1,:),L23(2,:),'k.'), hold on, plot(L23(1,:),L23(3,:),'k.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L24(1,:),L24(2,:),'w.'), hold on, plot(L24(1,:),L24(3,:),'w.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L25(1,:),L25(2,:),'g.'), hold on, plot(L25(1,:),L25(3,:),'g.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L26(1,:),L26(2,:),'r.'), hold on, plot(L26(1,:),L26(3,:),'r.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L27(1,:),L27(2,:),'b.'), hold on, plot(L27(1,:),L27(3,:),'b.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L28(1,:),L28(2,:),'c.'), hold on, plot(L28(1,:),L28(3,:),'c.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L29(1,:),L29(2,:),'m.'), hold on, plot(L29(1,:),L29(3,:),'m.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L30(1,:),L30(2,:),'y.'), hold on, plot(L30(1,:),L30(3,:),'y.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L31(1,:),L31(2,:),'k.'), hold on, plot(L31(1,:),L31(3,:),'k.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L32(1,:),L32(2,:),'w.'), hold on, plot(L32(1,:),L32(3,:),'w.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L33(1,:),L33(2,:),'g.'), hold on, plot(L33(1,:),L33(3,:),'g.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L34(1,:),L34(2,:),'r.'), hold on, plot(L34(1,:),L34(3,:),'r.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L35(1,:),L35(2,:),'b.'), hold on, plot(L35(1,:),L35(3,:),'b.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L36(1,:),L36(2,:),'c.'), hold on, plot(L36(1,:),L36(3,:),'c.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L37(1,:),L37(2,:),'m.'), hold on, plot(L37(1,:),L37(3,:),'m.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L38(1,:),L38(2,:),'y.'), hold on, plot(L38(1,:),L38(3,:),'y.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L39(1,:),L39(2,:),'k.'), hold on, plot(L39(1,:),L39(3,:),'k.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L40(1,:),L40(2,:),'w.'), hold on, plot(L40(1,:,L40(3,:),'w.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L41(1,:),L41(2,:),'g.'), hold on, plot(L41(1,:),L41(3,:),'g.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L42(1,:),L42(2,:),'r.'), hold on, plot(L42(1,:,L42(3,:),'r.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L43(1,:),L43(2,:),'b.'), hold on, plot(L43(1,:,L43(3,:),'b.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L44(1,:),L44(2,:),'c.'), hold on, plot(L44(1,:,L44(3,:),'c.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L45(1,:),L45(2,:),'m.'), hold on, plot(L45(1,:,L45(3,:),'m.')
axis([48 60 0 30])
grid on
%
figure
%
plot(L46(1,:% BPS_BPF_Q
III. GNSS Frequency Spectrum

% Plot the GNSS Power Spectrums
% Chris Bartone, Jan 2006
clear all; close all;
L1 = 1575.42;   % in units of [MHz]
L2 = 1227.60;   % in units of [MHz]
L5 = 1176.45;   % in units of [MHz]
E5 = 1191.795;  % in units of [MHz]
E5a = L5;       % in units of [MHz]
E5b = 1207.14;  % in units of [MHz]
E6 = 1278.75;   % in units of [MHz]
Ac = 1;
Rca = 1.023;    % in units of [MHz]
Tca = 1/Rca;    % in units of usec
Tcep = Tca./10; % in units of usec
fs = 10;fc = 5; % for BOC(10,5), M-Code
minf = -20*Rca; step_f_size = 0.001; maxf = 20*Rca;
f = minf:step_f_size:maxf;
ymin = -40; ymax = 0;
figure(1)   % plot L1 GPS spectrums
PSDca = Ac.*Ac.*Tca.*sin(pi.*f.*Tca)./(pi.*f.*Tca).^2; PSDca_dB = 10.*log10(PSDca); MAXca_dB = max(PSDca_dB);
PSDp = Ac.*Ac.*Tcp.*sin(pi.*f.*Tcp)./(pi.*f.*Tcp).^2; PSDp_dB = 10.*log10(PSDp); MAXp_dB = max(PSDp_dB);
Gboc = fc.*((tan(pi.*f.)/(2.*fs)).*sin(pi.*f./fc))./(pi.*f).^2; Gboc_dB = 10.*log10(Gboc); MAXboc_dB = max(Gboc_dB); % for n even from [1]
plot(f+L1,PSDca_dB-MAXca_dB,'m-');hold;
title('Normalized GPS L1 Power Spectrum');xlabel('frequency, [MHz]');ylabel('Normalized Power Spectral Density, [dB/Hz]');
plot(f+L1,PSDp_dB-MAXca_dB,'k-');
plot(f+L1,Gboc_dB-MAXca_dB,'r-');
axis([L1+minf,L1+maxf,ymin,ymax]); hold off;
figure(2) % plot L2 GPS spectrums
plot(f+L2,PSDca_dB,'g-');hold;
title('Normalized GPS L2 Power Spectrum');xlabel('frequency, [MHz]');ylabel('Normalized Power Spectral Density, [dB/Hz]');
plot(f+L2,PSDp_dB-MAXca_dB,'k-');
plot(f+L2,Gboc_dB-MAXca_dB,'r-');
axis([L2+minf,L2+maxf,ymin,ymax]); hold off;
figure(3) % plot L5 spectrum
plot(f+L5,PSDp_dB-MAXca_dB+6.'g-'); hold on;
title('Normalized GPS L5 Power Spectrum');xlabel('frequency, [MHz]');ylabel('Normalized Power Spectral Density, [dB/Hz]');
axis([L5+minf,L5+maxf,ymin,ymax]); hold off;
figure(4) % GPS signals all on one subplot(4,1,1)
plot(f+L1,PSDca_dB-MAXca_dB,'m-');hold;
plot(f+L1,PSDp_dB-MAXca_dB,'c-');
plot(f+L1,Gboc_dB-MAXca_dB,'r-');
plot(f+L2,PSDca_dB,'g-');
plot(f+L2,PSDp_dB-MAXca_dB,'c-');
plot(f+L2,Gboc_dB-MAXca_dB,'b-');
% NOW PLOT Galileo Signals

% NOW PLOT Galileo Signals

figure(5) % plot L1 Galileo spectrum
fs=1;fc=1; % for BOC(1,1), Galileo E1F signal
n=2*fs/c
Tc = Tca/fc; % units of usec
Gboc_L1F = (1./Tc).*((sin(pi.*f.*Tc./n).*sin(pi.*f.*Tc))./(pi.*f.*cos(pi.*f.*Tc./n))).^2; % for n even from [2]
Gboc_L1F_db = 10.*log10(Gboc_L1F); MAXboc_L1F_db = max(Gboc_L1F_db);
Gboc_L1F_boc11 = (1./Tc).*((sin(pi.*f.*Tc./n).*sin(pi.*f.*Tc))./(pi.*f.*cos(pi.*f.*Tc./n))).^2; % for n even from [2]
fs=6;fc=1; % BOC(6,1)
Tc = Tca/fc; % units of usec
Gboc_L1F_boc61 = fc.*((tan(pi.*f./(2.*fs)).*sin(pi.*f./fc))./(pi.*f)).^2; % for n even from [1]
Gboc_L1F_db = 10.*log10((10/11)*(Gboc_L1F_boc11) + (1/11)*Gboc_L1F_boc61 ); % MBOC(6,1,1/11)
MAXboc_L1F_db = max(Gboc_L1F_db);

fs = 15;fc = 2.5,n=2*fs/fc  % for BOC(15,2.5) Galileo E1P code
Tc = Tca/fc; % units of usec
Gboc_cos=(sin(pi.*f.*Tc).*(cos(pi.*f.*Tc./n)-1)./(pi.*f.*cos(pi.*f.*Tc./n))).^2./Tca; % for n even from [2]
Gboc_cos_db = 10.*log10(Gboc_cos); MAXboc_cos_db = max(Gboc_cos_db);
plot(f,L1,Gboc_L1F_db-MAXboc_L1F_db,'g-');hold on;
plot(f,L1,Gboc_cos_db-MAXboc_L1F_db,'r-');hold;
title('Normalized Galileo E1 Power Spectrum');xlabel('frequency, [MHz]');ylabel('Normalized Power Spectral Density, [dB/Hz]');
axis([L1+minf,L1+maxf,ymin,ymax]);hold off;
figure(6) % plot Galileo E6 spectrum
Rc_e6 = 5.115; % in units of MHz
Tc_e6 = 1/Rc_e6     % in units of usec
PSDe6 =Ac.*Ac.*Tc_e6.*(sin(pi.*f.*Tc_e6)./(pi.*f.*Tc_e6)).^2; PSDe6_dB = 10.*log10(PSDe6); MAXe6_db = max(PSDe6_db);
fs=10;fc=5; % for BOC(10,5), Galileo E6P signal
n=2*fs/fc
Tc = 1/(Rc_e6.*fc) % in units of usec
Gboc_E6P = (1./Tc).*((cos(pi.*f.*Tc./n).*cos(pi.*f.*Tc))./(pi.*f.*cos(pi.*f.*Tc./n))).^2; % for n even from [2]
Gboc_E6P_db = 10.*log10(Gboc_E6P); MAXboc_E6P_db = max(Gboc_E6P_db);
plot(f,E6,PSDe6_dB-MAXboc_L1F_db,'b-');hold on;
plot(f,E6,Gboc_E6P_db-MAXboc_L1F_db,'r-');hold;
title('Normalized Galileo E6 Power Spectrum');xlabel('frequency, [MHz]');ylabel('Normalized Power Spectral Density, [dB/Hz]');
axis([E6+minf,E6+maxf,ymin,ymax]);hold off;

fs = 15;fc = 10; n=2*fs/fc ;  % thus n is odd
GaltBOC=(8./(Tc.*(pi.*f_e5.^2))).*((cos(pi.*f_e5.*Tc))./(cos(pi.*f_e5.*Tc./n))).^2.*(1-cos(pi.*f_e5.*Tc./n));
GaltBOC_db = 10.*log10(GaltBOC); MAXaltBOC_db = max(GaltBOC_db);
plot(f_e5+E5,GaltBOC_dB-MAXboc_L1F_db,'b.');hold on;
title('Normalized Galileo E5 Power Spectrum');xlabel('frequency, [MHz]');ylabel('Normalized Power Spectral Density, [dB/Hz]');
axis([E5+minf_e5,E5+maxf_e5,ymin,ymax]);hold off;
figure(7) % plot E5 signal minf_e5 = -45*Rca; step_f_size = 0.001; maxf_e5 = 45*Rca;
f_e5 = minf_e5:step_f_size/2:maxf_e5;
figure(7) % plot E5 signal minf_e5 = -45*Rca; step_f_size = 0.001; maxf_e5 = 45*Rca;
fs = 15;fc = 10; n=2*fs/fc ;  % thus n is odd
GaltBOC=(8./(Tc.*(pi.*f_e5.^2))).*((cos(pi.*f_e5.*Tc))./(cos(pi.*f_e5.*Tc./n))).^2.*(1-cos(pi.*f_e5.*Tc./n));
GaltBOC_db = 10.*log10(GaltBOC); MAXaltBOC_db = max(GaltBOC_db);
plot(f_e5+E5,GaltBOC_dB-MAXboc_L1F_db,'b.');hold on;
title('Normalized Galileo E5 Power Spectrum');xlabel('frequency, [MHz]');ylabel('Normalized Power Spectral Density, [dB/Hz]');
axis([E5+minf_e5,E5+maxf_e5,ymin,ymax]);hold off;
figure(8) % All Galileo Signals Only
% subplot(4,1,1)
plot(f,L1,Gboc_L1F_db-MAXboc_L1F_db,'g-');hold on;
plot(f,L1,Gboc_cos_db-MAXboc_L1F_db,'r-');hold;
plot(f,E6,PSDe6_db-MAXboc_L1F_db,'b-');hold;
plot(f,E6,Gboc_E6P_db-MAXboc_L1F_db,'r-');hold;
plot(f_e5+E5,GaltBOC_dB-MAXboc_L1F_db,'b-');
title('Normalized Galileo Power Spectrum'); xlabel('frequency, [MHz]'); ylabel('Normalized PSD, [dB/Hz]');
axis([L5+minf,E6+maxf,ymin,ymax]); hold off;
axis([L5+minf,E6+maxf,ymin,ymax]); hold off;
IV. Create a definition file for 'N-Port'

% file=[0 0 0 0 0 0 0 0 0 0]
% contains in items in the following order
% freq IL12 IL13 IL14 Iso23 Iso24 Iso34 VSWR1 VSWR2 VSWR3 VSWR4
% S-Param from insertion loss, isolation and VSWR
% clear all
% format long g
[fileen pathn] = uigetfile("*.txt");
file = load([pathname filen]);
IL = file(:,2:4); % Insertion Loss
RL = file(:,end-2:end); % return loss
I = file(:,5:7); % Isolation
RL_db = [RL RL(:,2)]; % here its assumed that S11 and S33 are same
% IL = file(:,2:4);
% VSWR = file(:,end-3:end);

%% process data
file_bk = file;
for i = 1:length(IL),
    RL_mag(i,:) = (VSWR(i,:)-1)./(VSWR(i,:)+1);
    RL_db(i,:) = (20*log10(RL_mag(i,:)));
    % Gain here is computed using Insertion Loss and return loss
    % where IL = -10*log10 [S21]^2 / [1-S11]^2 ;
    S21(i,1) = sqrt(10^(IL(i,1)/10).*(1-(RL_mag(i,1)^2)));
    S31(i,1) = sqrt(10^(IL(i,2)/10).*(1-(RL_mag(i,1)^2)));
    S41(i,1) = sqrt(10^(IL(i,3)/10).*(1-(RL_mag(i,1)^2)));
    S21_db(i,1) = -1*(20*log10(S12(i,1)));
    S31_db(i,1) = -1*(20*log10(S13(i,1)));
    S41_db(i,1) = -1*(20*log10(S14(i,1)));
end

%% to file
fid1 = fopen('mcsplit3_edit.s4p','W');
% fid1 = fopen('atten.s2p','W');
fprintf(fid1,'%s
%s
','# MHz S DB R 50','!mcsplit.s3p');
fprintf(fid1,'%s
%s
','# MHz S MA R 50','!mcsplit.s4p');
for i=1:length(IL),
    % file(i,5:7)=[10^(file_bk(i,5)/20) 10^(file_bk(i,6)/20) 10^(file_bk(i,7)/20)];
    fprintf(fid1,'%d %f %d %f %d %f %d %f %d %f %d %f %d
',file(i,1), RL_db(i,1),S12_db(i,1),S13_db(i,1),S14_db(i,1));
    fprintf(fid1,'%d %f %d %f %d %f %d %f %d %f %d %f %d
',S12_db(i,1),RL_db(i,2),L(i,1),L(i,2));
    fprintf(fid1,'%d %f %d %f %d %f %d %f %d %f %d %f %d
',S13_db(i,1),L(i,1),RL_db(i,3),L(i,3));
    fprintf(fid1,'%d %f %d %f %d %f %d %f %d %f %d %f %d
',S14_db(i,1),L(i,2),L(i,3),RL_db(i,4));
end

%% for 4-port nw
fprintf(fid1,'%d %f %d %f %d %f %d %f %d %f %d %f %d %f %d %f %d
',file(i,1),RL_db(i,1),0,S21_db(i,1),0,S31_db(i,1),0,S41_db(i,1),0);
fprintf(fid1,'%d %f %d %f %d %f %d %f %d %f %d %f %d %f %d %f %d
',S21_db(i,1),0,RL_db(i,2),0,-L(i,1),-L(i,2),0);
fprintf(fid1,'%d %f %d %f %d %f %d %f %d %f %d %f %d %f %d %f %d
',S31_db(i,1),0,-L(i,1),0,RL_db(i,3),0,-L(i,3),0);
fprintf(fid1,'%d %f %d %f %d %f %d %f %d %f %d %f %d %f %d %f %d
',S41_db(i,1),0,-L(i,2),0,-L(i,3),0,RL_db(i,4),0);

%% for 3-port nw
fprintf(fid1,'%d %f %d %f %d %f %d %f %d %f %d %f %d %f %d %f %d
',file(i,1),RL_db(i,1),0,S12_db(i,1),0,S13_db(i,1),0);
fprintf(fid1,'%d %f %d %f %d %f %d %f %d %f %d %f %d %f %d %f %d
',S12_db(i,1),0,RL_db(i,2),0,-file(i,4),90);
fprintf(fid1,'%d %f %d %f %d %f %d %f %d %f %d %f %d %f %d %f %d
',S13_db(i,1),0,-file(i,4),90,RL_db(i,3),0);

%% for 2 port nw
fprintf(fid1,'%d %f %d %f %d %f %d %f %d %f %d %f %d %f %d %f %d
',file(i,1),RL_db(i,1),0,S12_db(i,1),-90);
fprintf(fid1,'%d %f %d %f %d %f %d %f %d %f %d %f %d %f %d %f %d
',S12_db(i,1),-90,RL_db(i,3),0,
зи
% fprintf(fid1,'%f %d %f %d
',S12_db(i,1),90,RL_db(i,2),0);

end
fclose(fid1);

Definition file for 'N-Port'
# GHz IL DB IS DB S DB R 50
!mcsplit3.s2p
!Data for 3-way Power-Split by Mini-Circuits
!Fq IL12 IL13 IL14 IS12 IS13 IS14 RL12 RL13 RL14
950  5.42  5.34  5.42 14.93 13.32 15.3  11.1 21.04  19.7
1000 5.37  5.29  5.37 15.99 13.99 16.38 11.91 21.04  20.18
1050 5.32  5.24  5.32 17.23 14.75 17.66 12.81 20.79  20.41
1100 5.28  5.19  5.28 18.74 15.64 19.23 13.9 20.24  20.37
1150 5.24  5.15  5.24 20.65 16.7 21.23 15.2 19.62  19.96
1200 5.21  5.12  5.22 23.15 17.95 23.86 16.68 19.07  19.59
1250 5.19  5.11  5.2 26.68 19.5 27.55 18.37 18.56  19.14
1300 5.19  5.1  5.2 31.4 21.43 31.87 19.89 18.26  18.75
1350 5.2  5.11  5.22 31.35 23.85 30.21 20.36 18.11  18.57
1400 5.23  5.14  5.25 26.27 26.57 25.45 19.18 18.14  18.49
1450 5.29  5.19  5.31 22.42 27.77 21.9 17.07 18.44  18.78
1500 5.37  5.28  5.4 19.61 25.76 19.26 14.81 19.03  19.18
1550 5.48  5.4  5.52 17.45 22.72 17.2 12.8 20.12  20.07
1600 5.64  5.56  5.68 15.72 20.1 15.54 11.01 21.67  21.
I. 3-Way Power Splitter in Ansoft Designer® - Return Loss, $S_{11}$ [dB] and Forward Gain, $S_{21}$ [dB], $S_{31}$ [dB] & $S_{41}$ [dB] for 3-Way Splitter in Ansoft Designer®
III. Bandpass Filter for GPS L1/Galileo E1 for Designer Approach I Simulated in Ansoft Designer® - Return Loss, S11 [dB] and Forward Gain, S21 [dB]
IV. Bandpass Filter for GPS L1/Galileo E1 for Designer Approach I Simulated in Ansoft Designer® - Group Delay, GD21 [ns]
V. Bandpass Filter for GPS L2C for Design Approach I Simulated in Ansoft Designer® - Return Loss, S11 [dB] and Forward Gain, S22 [dB]
VI. Bandpass Filter for GPS L2C for Design Approach I Simulated in Ansoft Designer® - Group Delay, GD21 [ns]
VII. Bandpass Filter for GPS L5/Galileo E5a for Design Approach I Simulated in Ansoft Designer® - Return Loss, S11 [dB] and Forward Gain, S22 [dB]
VIII. Bandpass Filter for GPS L5/Galileo E5a for Design Approach I Simulated in Ansoft Designer® - Group Delay, GD21 [ns]