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COMPASS/BEIDOU-2 STUDIES: ACQUISITION OF REAL-FIELD SATELLITE SIGNALS

Master's thesis

Examiner: Associate Professor Elena-Simona Lohan
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Contents

Abstract

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With the ever-increasing interests and demands of navigation and positioning services, Global Navigation Satellite Systems (GNSS) has been drawing more and more attention. Each every country or continent is trying to establish their own GNSS system. Compass, also known as Beidou-2, which is developed by China is one of the most popular GNSS in Asian continent. Compass project was started in 2000 and until now, there has been rather few public information regarding Compass. In order to test and analyse Compass, it is necessary to obtain the existing information about Compass. In addition, acquisition and navigation are the main parts of Compass system so that to acquire the signal and extraction the navigation message in a fast and accurate way is very important.

In this thesis, the Compass signals and receivers as well as three important segments of Compass systems are discussed. In addition, possible methods to achieve acquisition of Compass signals are illustrated. Meanwhile, a simulator is carried out to simulate the acquisition of Compass real-time field signals. The simulation results show that the parallel code phase search algorithm can be used to acquire Compass signals.

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List of Abbreviations

ADC	Analog-to-Digital Converter
AFSCN	Air Force Satellite Control Network
AGC	Automatic Gain Control
BDT	BeiDou Time
BPSK	Binary Phase Shift Keying
C/A	Coarse/Acquisition
CDMA	Code Division Multiple Access
CGCS2000	China Geodetic Coordinate System 2000
CTP	Conventional Terrestrail Pole
CTRS	Conventional Terrestrial Reference System
DC	Direct Current
DFT	Discrete Fourier Transform
ECEF	Earth-Centered, Earth-Fixed
FDMA	Frequency Division Multiple Access
FFT	Fourier-Frequency Transform
FLL	Frequency Lock Loop
GCC	Galileo Control Center
GCS	Galileo Control System
GEO	Geostationary Earth Orbit
Glonass	GLObalnava NAvigatsionnaya Sputnikovaya Sistema
GMS	Galileo Mission System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IERS	Reference System Service
IF	Intermediate Frequency
IFFT	Inverse Fast Fourier Transform
IGSO	Inclined Geosynchronous Orbit
IRM	Reference Meridian
IRP	Reference Pole
LFSR	Linear Feedback Shift Register
LHCP	Left-Hand Circularly Polarize
LNB	Low-Noise Block

MEO	Medium Earth Orbit
NAV	Navigation
NCO	Numerically Controlled Oscillator
NGA	National Geospatial-Intelligence Agency
NH	Neumann-Hoffman
PLL	Phase Lock Loop
PRN	Pseudorange
PRS	Public Regulated Service
RF	Radio Frequency
RHCP	Right-Hand Circularly Polarize
SNR	Signal-to-Noise Ratio
TT&C	Telemetry, Tracking and Command Center
UTC	Coordinated Universal Time
VDC	Volts of Direct Current
VSWR	Voltage Standing Wave Ratio
WGS84	World Geodetic System 1984

List of Symbols

a	Semi-major Axis
φ	Phase Difference
$\varphi(t)$	Phase
φ_{B1}	Compass B1 Carrier Initial Phase
φ_l	Latitude
λ	Longitude
μ_{CGCS}	Geocentric Gravitational Constant
ω	Argument of Perigee
ω_c	Carrier Frequency
ω_E	Earth's Angular Velocity
ω_{IF}	Intermediate Frequency
Ω	Right Ascension of Ascending Node
Ω_e	Rate of Earth Rotation
A	Amplitude
BW	Bandwidth of Filter
c	Speed of Light
C	Ranging Code
D	Data Modulated on Ranging Code
$D^k(n)$	Navigation Data
e	Eccentricity
f	Flattening
f_0	Carrier Frequency of Compass B1 Signal
f_{center}	Center Frequency of Filter
F_n	Noise Figure of n^{th}Element
F_{system}	System Noise Figure
G	C/A Code
G_n	Gain of n^{th}Element
GM	Earth's Gravitational Constant
h	Height
i	Inclination
M	Mean Anomaly
p	Intermediate Parameter
Q	Quality Factor
$S^j(t)$	Compass B1 Signal
$v(t)$	Transmitted Signal
$v_i(t)$	In-phase Component
$v_q(t)$	Quadrature Component
X	Number of Compass Satellite

1 Introduction

In the era of technological innovations and trends, the satellite navigation system became one of the indispensable techniques for us to unravel and discover the world. It is currently being used thoroughly in an effort to provide precise position information in public transportation, marine as well as aerospace. It is also applied to military, geological prospecting, geodetic and radio navigation field. It not only brings enormous economic interest, but also motivate the construction of national economy. During the sever earthquake happened in Wenchuan, China 2008, all the communication, electricity and transportations are damaged so that no information about the situation in the disaster area was able to obtained. Fortunately, by using the short message service of Compass, the disaster area was finally able to communicate with the outside. Thus, each every country is willing to develop their own satellite navigation system. The satellite navigation system is able to meet the positioning as well as timing requirements of moving objects no matter they are in the air, sea or on the land. [1]

Currently, the major satellite navigation system includes Galileo from Europe, Glonass from Russia and GPS from the United States with GPS being the most popular system in the world. All those satellite navigation systems only provide relatively low accuracy navigation service to public while the high accuracy service is encrypted and cannot be used by everyone. Thus, starting from the point of security, many countries are willing to set up their own satellite navigation system to overcome this issue. China has started Compass project from 1994 with first an experimental system called Beidou-1 and then is switched to Compass in 2000. It was first aimed at providing regional services to Asia-Pacific area and then covering the globe step by step. It is obvious that upon Asia-Pacific, there would be a competition between Compass and GPS. Compared to Galileo which currently operating 14 satellites, Compass grows rapidly from the moment the project started. [1]

By the end of 2012, Compass managed to cover whole Asia-Pacific area. From December 27th, 2012, upon the original short message communication, active positioning and two-way timing services, Compass is also able to provide navigation, timing, and continuous passive positioning services to users within Asia-Pacific with zero costs for civilization usage. [1]

Compass satellite navigation system is specifically designed to deliver high quality global positioning, navigation as well as timing services to users, either authorized or via open services. The concept of Open Services clearly defines that global positioning and timing services will be provided free of charge with an accuracy of 10 meters for positioning and 10 ns for timing service. For authorized service, there is currently no exact figure about the accuracy but it is said to be centimetre-level after Compass is fully completed.

1.1 Thesis Objectives

The aim of the work described in this scientific report is to present in a unified form the existing information about the Compass system and to make a basic analysis of the acquisition structures valid for Compass. Compass is a huge scientific project introduced and still under development by China, therefore the information available to public is strictly controlled and limited. Consequently, in order to test, investigate and further develop, the basic information of Compass needs to be obtained.

1.2 Thesis Contribution

The major contribution of the thesis is to give both general and detailed information regarding Compass satellite navigation system in order for future study and experiments. In addition, a Matlab-based simulator had been carried out in order to simulate the acquisition function of Compass.

1.3 Thesis Outline

Chapter 1 states the background and motivation of this thesis as well as the objectives, contribution and thesis outline.

Chapter 2 gives the brief introduction of Global Navigation Satellite System as well as four main navigation satellite systems nowadays in the world.

Chapter 3 explains Compass in details, including space segments, ground segments and user segments of Compass. In addition, theory of acquisition simulation method used in this thesis is illustrated. Meanwhile, different method that can be used for Compass tracking are discussed.

Chapter 4 illustrates the Compass B1 signal structure as well as the generation of Compass ranging code. Meanwhile, the structure of Compass navigation message is also explained.

Chapter 5 presents how the position is calculated by using the data collected from acquisition and tracking process.

Chapter 6 performs the simulation by Matlab of front-end and acquisition of Compass with real-field data.

Chapter 7 introduces further research that can be carried out regarding Compass, mainly about tracking process.

Chapter 8 concludes this thesis.

2 Global Navigation Satellite System (GNSS)

A global navigation satellite system (GNSS) is a type of system which provides positioning services with global coverage. Figure 1 below describes the classification of both global and regional Navigation Satellite Systems, where the national flag in each categorized column indicates which country the satellite system belongs to. The global systems include the Global Positioning System (GPS) from the United States, Glonass from Russia, Galileo from Europe and Compass or Beidou-2 from China. In addition to these countries, the United States and Europe have also constructed augmentation systems in order to be able to improve the performance of their global systems. Finally, Japan and India from the Asian region have developed their own regional and augmentation systems in an attempt to increase the reliability and accuracy of the already existing GPS system. The aim of the work described in this thesis is to describe and provide a better understanding of the Compass/Beidou-2 system, referred from now on as simply Compass.

Figure 1 *GNSS Classification [2]*

As of December, 2015, only GPS and Glonass systems are globally operational. Compass is currently in the process of extending itself into a global navigation system by 2020. On the other hand, Galileo is also intended to become a global system by 2020, too.

In general, all the global navigation satellite systems are comprised of a three-segment architecture: a space, a control and a user segment. The space segment refers to the operational satellites that are responsible for transmitting the radio signals to the users as well as accommodating the uplink and downlink satellite links. The control segments are positioned on the ground and consist of control and monitoring stations designed to track and monitor the satellites and to send and receive signals from the satellites. In addition, the control segment also provides the necessary functions to process the information obtained from the satellites for more complicated data analysis. Finally, the user segment generally refers to all the devices utilized by users which have a GNSS chipset incorporated, such as cellphones, cars etc.

In this chapter, Global Positioning System, Glonass and Galileo are briefly introduced while Compass is explained in more detail in the following chapter.

2.1 Global Positioning System (GPS)

The Navstar Global Positioning System, was built and it is currently being managed and maintained by the United States. It has the advantages of providing high accuracy and efficiency as well as low cost so that it is widely used in all fields. GPS has started as an American military project in 1958. In the 1970s, the United States army developed a new generation of GPS aimed at providing time and location services under all weather conditions as well as for other military purposes. By 1994, GPS became a satellite constellation with 24 satellites proving an estimated coverage of 98% of the earth. [42]

The GPS space segment originally was composed of 24 satellites (21 are operational and 3 are backup satellites) transmitting radio signals to users. Nowadays, GPS system has 32 satellites on sky (31 operational). The GPS satellites are positioned 20,200 kilometers above the earth with an orbit inclination of 55 degrees while being distributed on 6 orbit planes. This constellation was built with the aim to be able to observe at least 4 satellites in any point of the Earth. However, northern latitudes are not well covered by GPS. If at least 4 satellites can be observed at a certain time, this would ensure that the GPS receiver acquires the correct geographic coordinate and the height of the observation point on the earth so that to perform navigation, positioning, timing and other services. The GPS technology can be used to lead aircrafts, cruises, vehicles as well as individuals arrive their destinations on time by following the pre-planned route accurately.

The control segment is made up of one master control station, several monitor stations and ground antennas to track satellites, monitor their transmissions, perform data analysis and send information to the constellation [3]. Figure 2 below shows the location of the control segment of GPS all over the world. The GPS master control station is located in Colorado, US and provides command and control functions of the GPS constellation. In addition, there is an alternative master control station in California for backup and redundancy. The monitor stations include six from the Air Force and eleven from the National Geospatial-Intelligence Agency (NGA) located all over the world, where they are able to track the satellites and send the observed data back to the originating point, the master control station. The ground antennas include four dedicated antennas at Kwajalein Atoll, Ascension Island, Diego Garcia and Cape Canaveral separately. Moreover, there are eight Air Force Satellite Control Network (AFSCN) remote tracking stations throughout the world connected to the control station.

The user segment of GPS refers to any applications which include a GPS receiver, are able to receive signals from the satellites as well as use the data received for analyzing the user's time and position.

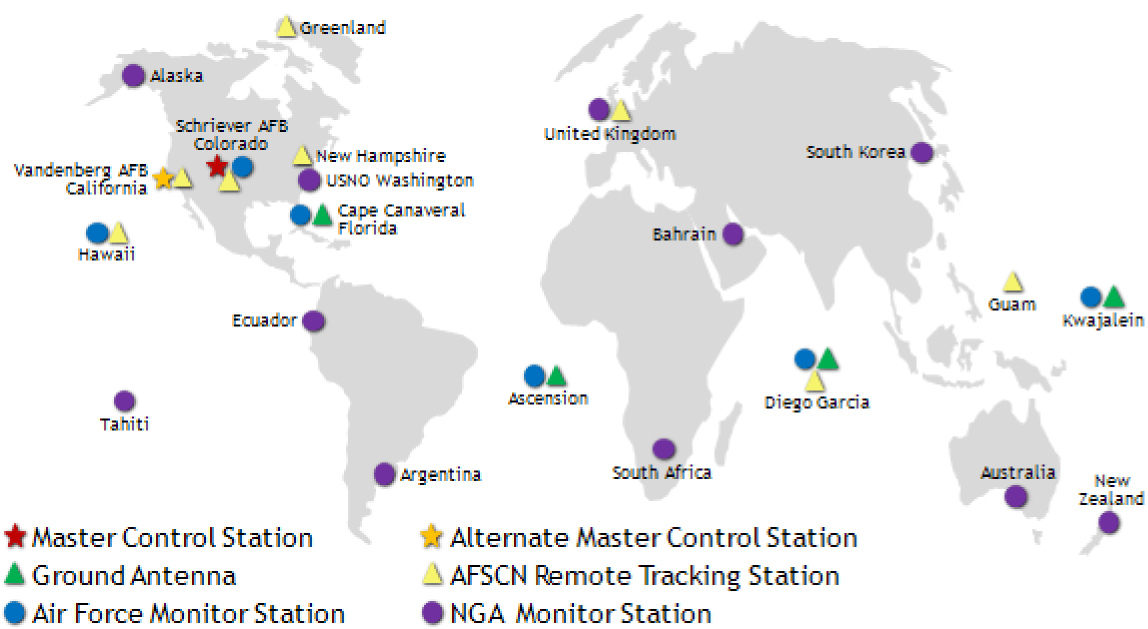

***Figure 2**. Control Stations of GPS [3]*

The principle of GPS is to measure the distance between the satellite, whose position is transmitted via ephemeris and almanac in the navigation data and the user's receiver. It will then combine all the information from multiple satellites to acquire the most precise position of the user. The coordinates of the satellite can be easily obtained from the time which was recorded by the satellite's borne clock in the satellite ephemeris. The distance between the user and the satellite is calculated by multiplying the time needed for the signal to traverse from the satellite to the user and the speed of light. Because there are delays due to the atmospheric ionized layer, to the troposphere and to other sources of interference such as multi-paths, the measured distance is not the real distance, it is just a pseudo-range. When the satellites are working properly, they keep sending navigation messages which are made of pseudo-random codes, identifying the satellites, and navigation data, including ephemeris (accurate satellite location) and almanac (coarse satellite location). There are several kinds of pseudo-random codes that are used by GPS. The two main ones are the C/A code which is for civilian, open-service use and the P(Y) code which is designed for military use. The frequency of C/A code is 1.023MHz with 1 millisecond repetition interval. The C/A code has a chip duration of about 1 microsecond, which translates to about 300m chip duration in distance. The frequency of P(Y) code is 10.23MHz with 266.4 days repetition interval, 0.1 microsecond chip duration (i.e-. 30m chip duration in distance). The navigation message contains information about the satellite ephemeris, working conditions, clock corrections, ionosphere delay corrections and atmospheric refraction corrections. This message is demodulated from the satellite's signal and sent at a rate of 50b/s on the carrier. When the user receives the navigation message, the time of the satellite will be then extracted and compared with the user's clock in order to get the distance between the user and the satellite. After that, with the use of the satellite ephemeris from the navigation message it will calculate the position of the satellite at the time the message was being sent. The position of the user in the WGS 84 (which will be discussed in details in Chapter 4) coordinate will be known.

Another action taken by the United States in order to meet the demands of GPS users as well as keep GPS services as competitive as possible internationally is the so-called GPS modernization. The modernization plan includes adding new GPS signals, developing new military GPS receivers in order to improve the capability of interference resistance, improving control segments and implementing GPS III plan.

The new signals introduced that are intended for civilian use are L2C, L5 and L1C. The implementation of L2C signal provides quicker signal acquisition, while having an improved reliability and maintaining a wider operating range. In addition to the above, L2C is broadcasting at a higher effective power which makes signals easier to be received without the interference from objects, both indoors and outdoors. L5 provides more power and wider bandwidth compared to the current civil GPS signals which improves the indoor reception significantly. Furthermore, L5 is broadcasting in a frequency band which is mainly reserved for safety services so that an aircraft signal will broadcast in L5 with the combination of L1 C/A in the future. L1C, which broadcasts at the frequency of 1575.42MHz, was designed to work together with Galileo.

2.2 Glonass

Glonass is the abbreviation of GLObalnaya NAvigatsionnaya Sputnikovaya Sistema (Russian); it is a global navigation system that is being managed by the Russian Aerospace Defense Forces. Glonass was first started to be built in 1976 by the Soviet Union and Russia renewed it by 2013. By year 2000, the Glonass system was able to provide coverage all over Russia and finally managed to provide satellite positioning services on a global scale by October 2011.

According to its implementation, the space segment of Glonass consists of 24 satellites located in a middle circular orbit with an altitude of 19,100 Km and an inclination of 64.8 degrees. As of May, 2016, there are in total 29 satellites with 24 satellites in operational mode, 2 in maintenance mode, 3 in spare (backup) mode and 1 in flight tests phase. [4]

The control segment of Glonass is consisted of a system control center which is located at Krasnoznamensk, Russia, a network of five telemetry, tracking and command centers (TT&C), a central clock located in Schelkovo, three upload stations, two laser ranging stations, a network of four monitoring and measuring stations as well as six additional monitoring and measuring stations. The system control center is specifically designed to control and manage the satellite constellation at the system level whereas the TT&Cs are responsible for sending and receiving radio signals from the satellites. The laser ranging stations provide Glonass with calibration data in order to be able to make ephemeris determination. [5]

The user segment refers to the devices that are able to receive the signals generated by the Glonass system and process the received data accordingly for the analysis and computation of the user’s coordinates with accurate time.

Traditionally, by distinction with GPS system, Glonass uses a frequency division multiple access (FDMA) method to distinguish between different satellites, while GPS is using code division multiple access (CDMA). Each Glonass satellite broadcasts on three different frequencies signals which are L1 = 1.602+0.5625K MHz, L2 = 1.246+0.4375K MHz and L5, while K indicates the frequency index of each every satellite. In addition, in order to interoperate with other GNSS systems, Glonass had introduced CDMA signals as well. The first CDMA signal, L3, coming with the launch of Glonass-K satellite is broadcasting at the frequency of 1207.14MHz. Another modernized Glonass satellite, Glonass-KM, will be launch by 2025 will based on the frequency of 1176.45MHz which is known as L5 signal. The L1-L2-L5 frequency bands of Glonass are closed to the L1-L2-L5 frequency bands of GPS.

2.3 Galileo

Galileo is a GNSS system which is considered at the time to be under development by the European Union as well as the European Space Agency. The system was named after the Italian astronomer Galileo Galilei. As the need of navigation systems continues to grow, Europe aims in building its own dedicated satellite system to diversify and be independent from the rest (GPS, Glonass and Compass systems). However, it is of major importance that the Galileo system is at the same time interoperable and fully compatible for integrating with these systems in an effort to increase the accuracy and reliability of future navigation services. Unlike GPS and Glonass, Galileo is currently being developed to be specifically under civilian control.

The space segment of Galileo is expected to provide a total of 30 satellites where 27 of them will be fully operational whereas the remaining 3 will be considered spare. The project is projected to be deployed by 2020. These satellites are positioned in three orbits above the Earth at 23,222 Km and an inclination of 56 degrees. The first two operational satellites were launched to validate the system on 21st of October 2011 with the following two launched on 12th of October 2012. Now the system has 12 satellites on sky, but two of them were launched in an incorrect orbit.

The control segment will be composed of two Galileo Control Centers (GCC) and a global network of transmitting and receiving stations (monitoring, TTC and uploading stations). Each GCC will be supported by a dedicated Galileo Control System (GCS) which will manage and maintain the necessary control functions for satellite constellation. In addition, a dedicated Galileo Mission System (GMS) will handle the determination and data transfer services.2.3 [6]

The Galileo navigation signals are transmitted in four different frequency bands which are known as E1, E6 and E5, which is then divided into E5a and E5b band with CDMA as the access technique. The E1 and E6 signals are transmitted in the frequency of 1575.42MHz and 1278.75MHz separately. Both of them consists of three channels which are PRS (public regulated service), data and pilot channel. The navigation data and ranging code within PRS channel are encrypted while pilot channel contains only a ranging code but not any navigation data stream. The E5 band, which is different than E1 and E6, is divided into another two frequency bands with each consists of a data and a

pilot channel. The E5 band is transmitted at the frequency of 1191.795MHz with the carrier frequency of E5a at 1176.45MHz and E5b at 1207.14MHz.
With Galileo system's high accuracy and reliability, the user segment will cover land, sea and air areas combined with a variety of different electronic devices.

2.4 Compass

Compass is the global navigation satellite system set up and currently under development by China. It is the third mature satellite navigation system after GPS and Glonass, according to [7], though different sources may place Galileo on third place too. It is consisted of the space, ground and user segment. The space segment includes 5 GEO satellites, 27 MEO satellites and 3 IGSO satellites; the ground segment includes the control station, acting as a master as well as the injection and monitor stations. The user segment is made up of Compass user terminal and other terminals which are also compatible with additional GNSS systems. The Compass navigation system provides high accuracy and reliability in positioning as well as improved navigation and timing services at any time to all users.

On 27th of December, 2012, Ran Chengqi, the press spokesman of Compass navigation system, announced that from that day, Compass officially started to provide services to Asia-Pacific area. The basic characteristics were 10 meters for horizontal and vertical positioning accuracy, 0.2 second for velocity precision, a two-way high precision timing as well as short message communication services. The overall performance is equivalent to GPS.

More details regarding Compass navigation satellite system is discussed in the following chapter.

3 Compass Signals and Receivers

In order to analyze the signals transmitted by the satellites, it is apparent that we need a better understanding of characteristics of the signal. In addition, it is also important to look into the part of the system that is receiving the signals since that is where the signal is being analyzed. In this chapter, both the signals and the design and functional of the receiver of Compass navigation satellite system will be discussed.

In "BeiDou Navigation Satellite System, Signal In Space, Interface Control Document, Open Service Signal (Version 2.0)" which was published by China satellite office in December 2013, the frequency and modulation method of B1I and B2I signals are discussed. This probably because B1Q, B2Q and B3 signal are only used for authorized services. According to this document, the carrier frequency of B1I and B2I is 1561.098 MHz and 1207.140 MHz respectively while both of them induce BPSK modulation.

In addition, as discussed in [45], more details regarding Compass signals had been illustrated. According to [45], there are three different signals – B1, B2 and B3 with B1 and B2 divided into I and Q phase respectively in the second phase of Compass. In the third phase of Compass, the three signals are further refined.

B1 and B2 are for civilian use while B3 is for military use. Table 1 below gives the illustrations of the second phase Compass signals, which have been used in the analysis part of this thesis. All these signals are modulated by BPSK.

Table 1. *Characteristics of Phase Two Compass Signals (used in the simulations part)*

Signal	Code Modulation	Carrier Frequency, MHz	Service
B1I	BPSK2	1,561.098	Open
B1Q	BPSK2	1,561.098	Authorized
B2I	BPSK10	1,207.140	Open
B2Q	BPSK10	1,207.140	Authorized
B3	BPSK10	1,268.520	Authorized

The newer signal structure is the one given in Phase three Compass signals and it is shown in Table 2. B1 is divided into B1-CD, B1-CP, B1D and B1P whose code modulation technique are BOC with together comprise a MBOC modulation. B2 is divided into B2-aD, B2-aP, B2-bD and B2-bP. The carrier frequency of B2aD and B2aP is at 1,176.45 MHz while 1,207.14 MHz for B2-bD and B2-bP. All of these four using BPSK 10 as modulation technique. B3 signal is for authorization use so not much information regarding this frequency band is revealed currently. [36][45]

Table 2. *Characteristics of Phase Three Compass signals*

Signal	Code Modulation	Carrier Frequency, MHz	Service
B1-CD	BOC or MBOC	1575.42	Open
B1-CP	BOC or MBOC	1575.42	Open
B1D	BOC	1575.42	Authorized
B1P	BOC	1575.42	Authorized
B2aD	BPSK 10	1,176.45	Open
B2aP	BPSK 10	1,176.45	Open
B2bD	BPSK 10	1207.14	Open
B2bP	BPSK 10	1207.14	Open
B3	QPSK 10	1268.52	Authorized
B3-AD	BOC	1268.52	Authorized
B3-AP	BOC	1268.52	Authorized

Among all the Compass signals, one main code modulation method used is BPSK. BPSK is the abbreviation of binary phase-shift keying. It is the simplest form of phase-shift keying which is a digital modulation method by changing the phase of the carrier wave to transmit data. As shown in Figure 3, in BPSK, two phases that are separated by 180 degree is used. In this figure, these two phases are located on the I-axis which is not a necessary condition as long as these two phases are in 180 degree difference. [32]

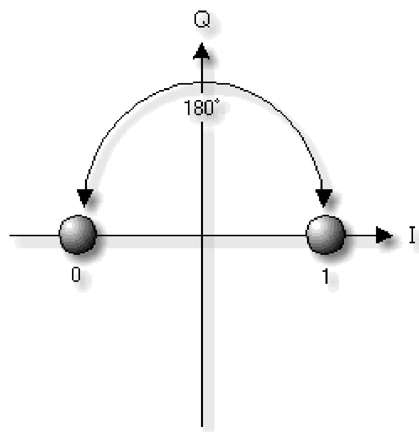

Figure 3. *BPSK [17]*

For different signals, the carrier frequencies are different. However, for the same signal, no matter which part it is, they obtain the same carrier frequency. As of the four signals in B2 frequency which are using BPSK (10), 10 indicates the chip rate.

BOC, which is binary offset carrier modulation, is to multiply another rectangular carrier wave to BPSK. Normally, BOC is denoted as BOC(m,n) with m indicates the frequency of the added carrier wave and n indicates the frequency of the BPSK chip frequency.

MBOC, which is multiplexed binary offset carrier modulation, is a modulation that combines a SinBOC(1,1) and SinBOC(6,1) together. MBOC is a general description of multiplexed signal, there are two major ways to achieve this modulation, either by CBOC or TMBOC. Composite BOC (CBOC) is a weighted sum or difference of BOC(1,1) and BOC(6,1). Time-multiplexing BOC (TMBOC) is for a given length of chips, certain chips are using BOC(6,1) while all the other chips are using BOC(1,1).

The modulation method that B2 signal obtain is Alternative BOC (AltBOC). AltBOC is a transformation of the traditional BOC modulation. The implementation is similar with BOC, however, in BOC, the two carrier needs to obtain same information while in AltBOC, they could carrier different information. [46]

3.1 Coordinate Frame

Different than GPS who is using WGS 84 as its coordinate frame, Compass's coordinate frame is based on China Geodetic Coordinate System 2000 which known as CGCS2000 in short. CGCS2000 was approved by the state council in April 2008 and started to put into effect from 1st of July, 2008.

The origin of CGCS 2000 is located in the center of mass; the Z-axis points to the direction of the reference pole (IRP) defined by International Earth Rotation and Reference System Service (IERS); the X-axis points to the intersection of the equatorial plane which passes through the origin as well as orthogonal with Z-axis and the reference meridian (IRM) defined by IERS; Y-axis forms a right handed orthogonal coordinate frame with X-axis and Z-axis.

The origin of CGCS2000 is also the geometrical center of CGCS2000 ellipsoid with Z-axis as the rotation axis of CGCS2000 ellipsoid. The fundamental constants of CGCS2000 ellipsoid are shown in table 2:

Table 3. *CGCS2000 fundamental constants*

Parameter	Value
Semi-major axis	a = 6378137.0m
Geocentric gravitational constant (including mass of earth atmosphere)	μ_{CGCS}= 3.986004418×10^{14} $\mathrm{m}^3/\mathrm{s}^2$
Flattening	f = 1/298.257222101
Rate of earth rotation	Ω_e=7.2921150×10^{-5}rad/s

3.2 Ranging Code

The ICD v2.0 which was published by China in December 2013 specify the Compass B1-I and B2-I ranging code which is a balanced Gold code truncated with the last one chip. ICD defines the chip rate of B1-I and B2-I ranging code is 2046 Mcps with a chip length of 2046. According to “Simulation and Design of Compass II Ranging Code Generator” [47], the chip length of Compass B3 signal is 10230 chips. In order to understand this ranging code, it is necessary to observe the Gold code first. Gold code, also known as Gold sequence, is a type of binary sequence, used in telecommunication and satellite navigation. [18] This code has bounded small cross-correlations property within a set. A set of Gold code consists of $2^n - 1$ sequences each one with a period of $2^n - 1$. For Compass B1-I and B2-I signal, n is equal to 11.

A set of Gold codes can be generated using a tapped linear feedback shift register (LFSR). Figure 4 gives the ranging code generator of Compass B1-I and B2-I signal. The ranging code generator is consists of two shift registers. The shift registers each have 11 cells generating sequences of length 2047. The two resulting 2047 chip-long sequences are modulo-2 added to generate a 2046 chip-long Gold code (The last one chip is truncated). [34]

Every 2047^{th} period, the shift registers are reset with all ones, making the code start over. The G1 sequence always has a feedback with the polynomial

$$G1(X) = 1 + X + X^7 + X^8 + X^9 + X^{10} + X^{11}$$

which means that state 1, state 7, state 8, state 9, state 10 and state 11 are fed back to the input. Meanwhile, the G2 sequence always has the polynomial

$$G2(X) = 1 + X + X^2 + X^3 + X^4 + X^5 + X^8 + X^9 + X^{11}$$

which means that state 1, state 2, state 3, state 4, state 5, state 8, state 9 and state 11 are fed back to the input.

In order to generate different ranging code for different satellites, the outputs of the two shift registers are combined in the following way. The G1 register always supplies its output while the G2 register supplies two of its states to a modulo-2 adder to generate its output. The selection of the states for the modulo-2 adder is called the phase selection as shown in the figure 4.

A shift register is a set of one bit memory cells. When a clock pulse is applied to the register, the content of each cell shifts one bit to the right. The content of the last cell is exported as output. The input to cell 1 is determined by the state of the other cells. In this case, for example,

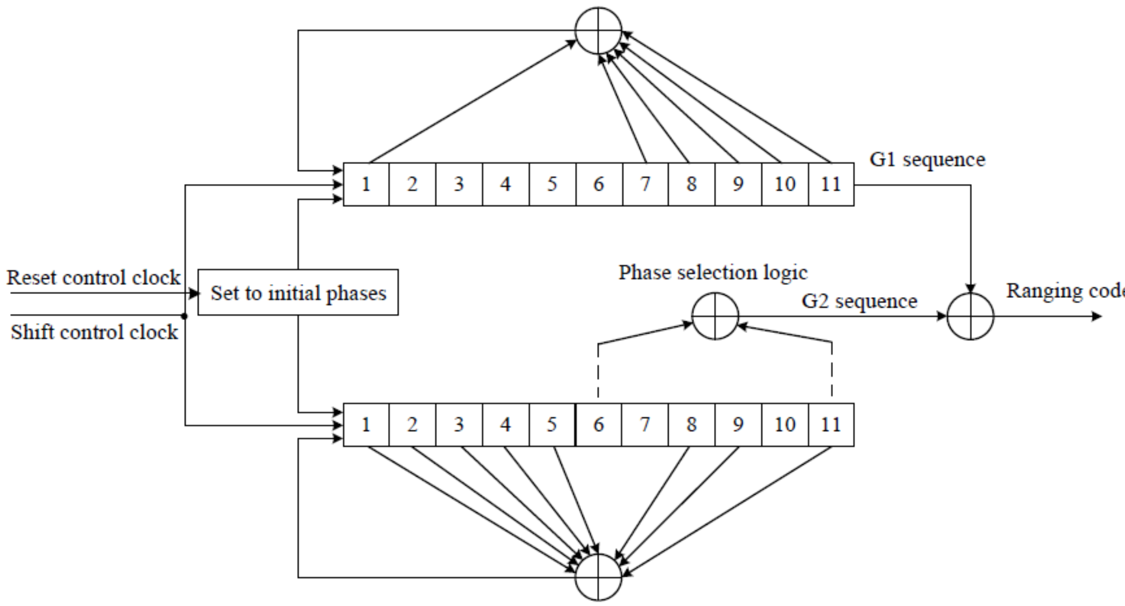

Figure 4. *Compass B1-I Signal Ranging Code Generator [19]*

Table 4. *Output of the exclusive OR operation*

Input1	Input2	Output
0	0	0
0	1	1
1	0	1
1	1	0

the binary sum from cells 1, 7, 8, 9, 10 and 11 in a 11-cell register could be the input. Depends on the different states of different cells, the results of the exclusive OR operation could be either 1 or 0. The properties of exclusive OR operation is shown in Table 3: if two states have the same value, the output is 0; otherwise, the output is 1. The result of the exclusive OR operation is then read into cell 1. If we start with 1 in each every cell, after 10 clock pulses, the contents will be 10001010101. The next clock pulse will take the contents in cell 1, 7, 8, 9, 10, 11 and place their sum, which is 0, in cell 1. Meanwhile, all other bits have shifted cell to the right, and the 1 in cell 11 becomes the next bit in the output.

The ranging code is generated by two 11-bit LFSRs of maximal length $2^{11} – 1$. One is the register that is just described above, the other one has $G2(X) = 1 + X + X^2 + X^3 + X^4 + X^5 + X^8 + X^9 + X^{11}$ in which cell 1, 2, 3, 4, 5, 8, 9, 10 and 11 are tapped and binary-added to get the new input for cell 1. Consider this register, the output comes not from cell 11 but from a second set of taps (as shown in table 4). Different pairs of these second taps are binary-added. The different pairs results in the same sequence except a different delay or shifts. This is due to the "shift and add" or "cycle and add" property which specifies that chip-by-chip sum of a maximal-length register sequence and any shift of itself results in the same sequence except for a shift. The delayed version of the G2 sequence is binary-added to the output of G1 which forms the ranging code.

Table 5. *Phase assignment of G2 sequence*

No.	Satellite Type	Ranging code number	Phase assignment of G2 sequence
1	GEO satellite	1	$1 \oplus 3$
2	GEO satellite	2	$1 \oplus 4$
3	GEO satellite	3	$1 \oplus 5$
4	GEO satellite	4	$1 \oplus 6$
5	GEO satellite	5	$1 \oplus 8$
6	MEO/IGSO satellite	6	$1 \oplus 9$
7	MEO/IGSO satellite	7	$1 \oplus 10$
8	MEO/IGSO satellite	8	$1 \oplus 11$
9	MEO/IGSO satellite	9	$2 \oplus 7$
10	MEO/IGSO satellite	10	$3 \oplus 4$
11	MEO/IGSO satellite	11	$3 \oplus 5$
12	MEO/IGSO satellite	12	$3 \oplus 6$
13	MEO/IGSO satellite	13	$3 \oplus 8$
14	MEO/IGSO satellite	14	$3 \oplus 9$
15	MEO/IGSO satellite	15	$3 \oplus 10$
16	MEO/IGSO satellite	16	$3 \oplus 11$
17	MEO/IGSO satellite	17	$4 \oplus 5$
18	MEO/IGSO satellite	18	$4 \oplus 6$
19	MEO/IGSO satellite	19	$4 \oplus 8$
20	MEO/IGSO satellite	20	$4 \oplus 9$
21	MEO/IGSO satellite	21	$4 \oplus 10$
22	MEO/IGSO satellite	22	$4 \oplus 11$
23	MEO/IGSO satellite	23	$5 \oplus 6$
24	MEO/IGSO satellite	24	$5 \oplus 8$

25	MEO/IGSO satellite	25	$5 \oplus 9$
26	MEO/IGSO satellite	26	$5 \oplus 10$
27	MEO/IGSO satellite	27	$5 \oplus 11$
28	MEO/IGSO satellite	28	$6 \oplus 8$
29	MEO/IGSO satellite	29	$6 \oplus 9$
30	MEO/IGSO satellite	30	$6 \oplus 10$
31	MEO/IGSO satellite	31	$6 \oplus 11$
32	MEO/IGSO satellite	32	$8 \oplus 9$
33	MEO/IGSO satellite	33	$8 \oplus 10$
34	MEO/IGSO satellite	34	$8 \oplus 11$
35	MEO/IGSO satellite	35	$9 \oplus 10$
36	MEO/IGSO satellite	36	$9 \oplus 11$
37	MEO/IGSO satellite	37	$10 \oplus 11$

Regarding gold codes, there is a very special characteristic of it that cannot be ignored. The most two important characteristics of the gold code are the correlation properties. The first one is known as nearly no cross correlation property which means all the gold codes are nearly uncorrelated with each other. The other property is that there is nearly no correlation except for zero lags between a gold code and itself. Figure 5 gives an example of these two properties. As explained before, there is a very high correlation at lag 0 when a gold code correlate with itself (the left picture) while low correlation when correlating with another gold code (the right picture).

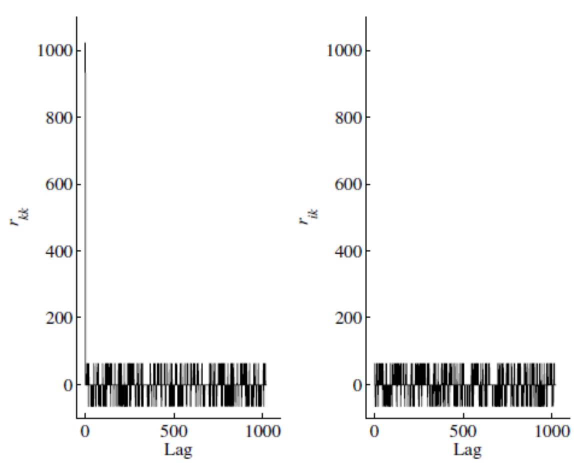

Figure 5. *Correlation properties of the gold codes [20]*

3.3 Navigation Message

The navigation message contains information regarding satellite orbits. The information is uploaded to all satellites from the ground stations. The Compass navigation messages are formatted in D1 and D2 based on their rate and structure. The rate of D1 navigation message is 50bps and it contains basic navigation information. The rate of D2 navigation message is 500bps and it contains not only basic navigation information but also augmentation service information.

For D1 navigation message, Neumann-Hoffman (NH) code is modulated on ranging code. One ranging code period corresponds to one bit duration of NH code while one NH code period corresponds to one navigation message bit. As shown in figure 6, the duration of one ranging code period is 1 millisecond and the one navigation message bit is 20 milliseconds. Accordingly, the length of NH code, whose content is 00000100110101001110, is 20 bits with rate of 1 kbps and bit duration of 1 millisecond.

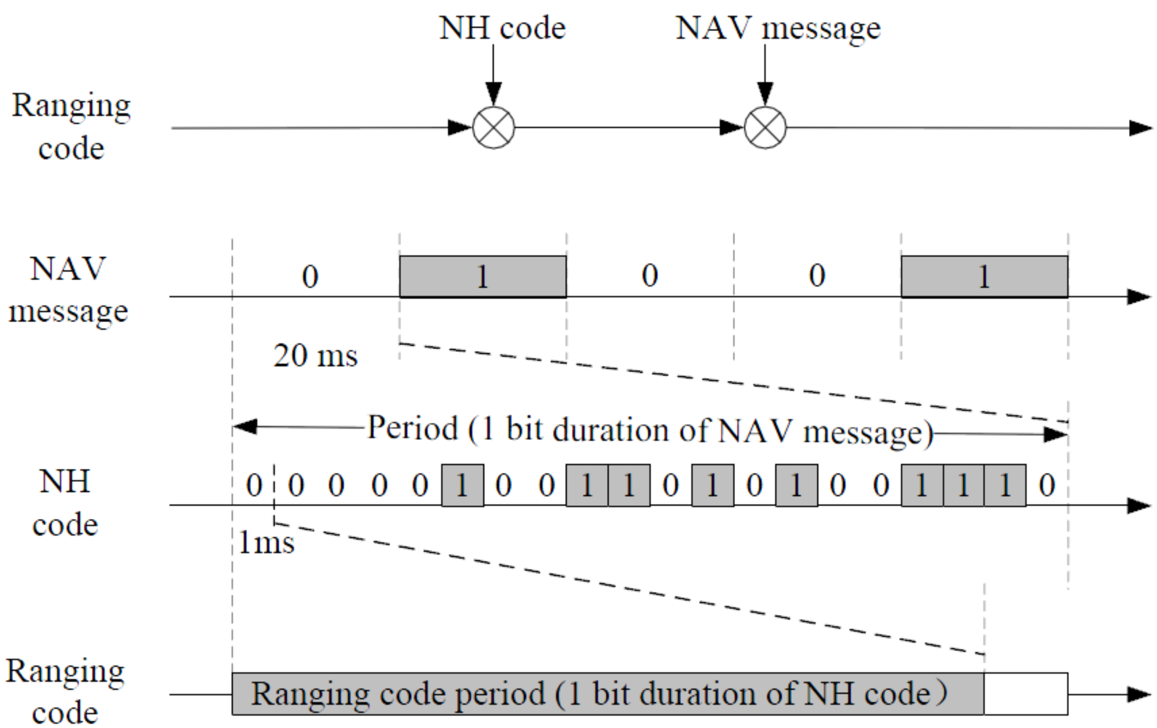

Figure 6. *NH code and its modulation to ranging code [21]*

The frame structure of D1 navigation message is shown in figure 7. It shows that the D1 navigation message is consists of superframes, frames and subframes. Subframes are formed by 10 words; each word has 30 bits and duration of 0.6 seconds. Each frame is formed by 5 subframes which results in a total length of 1500 bits and duration of 30 seconds. Likely, each superframe is 36000 bits long which means it is consists of 24 frames and duration of 12 minutes.

As discussed before, D1 navigation message contains basic navigation information including fundamental navigation information of the broadcasting satellites which are seconds of week, week number, user range accuracy index, autonomous satellite health flag, ionospheric delay model parameters, satellite ephemeris parameters and their age, satellite clock correction parameters and their age and equipment group delay differential. In addition, it also contains almanac and BeiDou navigation satellite system Time (BDT) offsets from other systems such as Coordinated Universal Time (UTC) and other navigation satellite systems.

The subframe 4 and 5 of D1 navigation message are swapped into 24 times each via 24 pages. Pages 1 to 24 of subframe 4 as well as pages 1 to 10 of subframe 5 are used to broadcast almanac and time offsets information from other systems while pages 11 to 24 of subframe 5 are reserved. On the contrary, subframe 1, 2 and 3 broadcasts the fundamental navigation information of the broadcasting satellite.

The frame structure of D2 navigation message is shown in figure 8 which is kind of alike with D1 navigation message. D2 navigation message is also composed of superframes, frames and subframes. Each subframe is consists of 10 words in which there are 30 bits and duration of

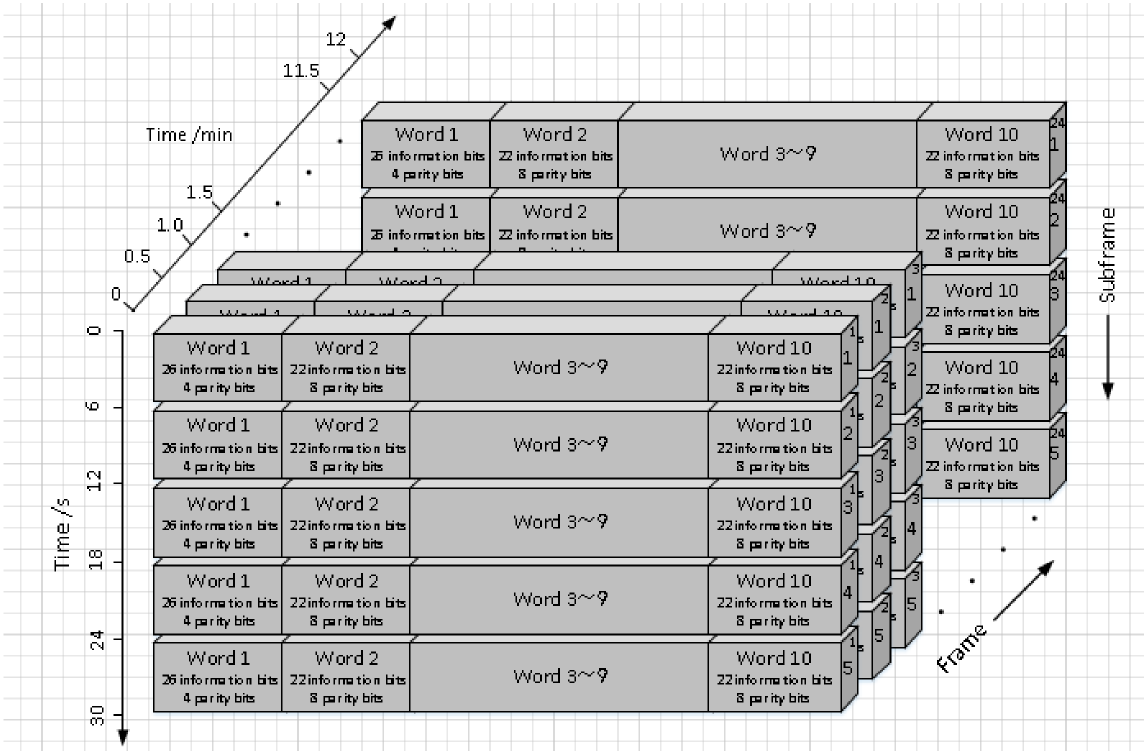

Figure 7. *Frame Structure of D1 Navigation Message*

0.06 second. Five subframes form a frame of length 1500 bits and duration of 3 seconds. A superframe is formed by 120 frames. The whole length of a superframe is 180,000 bits with duration of 6 minutes.

The information covered by D2 navigation message are the basic navigation information of the broadcasting satellite, almanac, time offset from other systems, integrity and differential correction information of Compass navigation system and ionospheric grid information. The first subframe is swapped into 10 times via 10 pages. The last subframe is swapped into 120 times via 120 pages. Subframes 2, 3 and 4 are swapped into 6 times each via 6 pages.

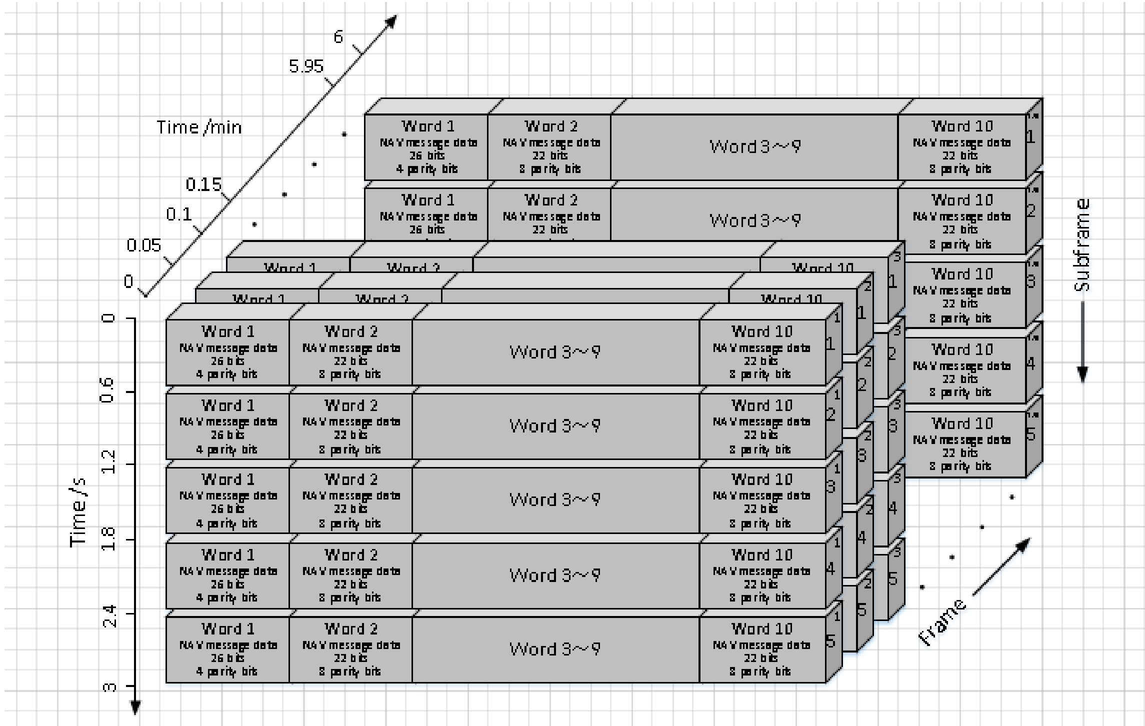

Figure 8. Frame Structure of D2 Navigation Message

4 Compass Navigation Satellite System

Compass Navigation Satellite System, also known as BeiDou-2 Navigation Satellite System, is a global satellite navigation system that is currently implemented by China. The Compass Navigation Satellite Test System was built in 1994 (initially called Beidou-1), and finally turned into an official production system in year 2000 after launching two Compass Navigation satellites. [40]

The Compass Navigation Satellite System aims at becoming an independent, open, advanced and stable navigation system which provides coverage for the entire world. The system will deliver high precision, reliable and more accurate positioning, as well as improved and assisted navigation and timing services for all users regardless of their location. [30]

There is a “Three-steps” plan when building the Compass Navigation Satellite System and it is still in processing phase. The first step defines the test period under which few Geostationary Earth Orbit (GEO) satellites are used to test and accumulate the experience for further development. The second step is to launch more than 10 satellites till 2012 to cover the Asia-Pacific region which is already completed currently and the final step is to expand the current regional navigation system into global. This is expected to be completed by 2020 with 5 Geostationary Earth Orbit (GEO) satellites, 27 Medium Earth Orbit (MEO) satellites and 3 Inclined Geosynchronous Orbit (IGSO) satellites. [7]

Compass Navigation Satellite System is divided into three major segments, as any other GNSS: the space, ground and user segment. In this chapter, the three segments of the Compass Navigation Satellite System are discussed in more detail.

4.1 Compass Space Segment

The initial Compass Navigation Satellite System (the Test System, also known as BeiDou-1) is a regional navigation system that provides fast positioning, short message communication and timing services. The system consists of two geostationary satellites (80ºE and 140ºE), one backup satellite on orbit (110.5ºE), a central control system, a calibration system and different users. When compared to GPS, this test system covers only a small part of China (70ºE to 140ºE and 5ºN to 55ºN). Meanwhile, the accuracy of the positioning and timing is also quite poor – around dozens of meters for positioning and 100 nanoseconds for timing. [31]

From 2007, the Compass Navigation Satellite System (also known as BeiDou-2) was really taken into construction and is still under development. The 5 GEO satellites are located at 58.75ºE, 80ºE, 110.5ºE, 140ºE and 160ºE separately. The 30 non-GEO satellites are divided into 27 Medium Earth Orbit (MEO) satellites and 3 Inclined Geostationary Earth Orbit (IGSO) satellites. Both the MEO satellites and the IGSO satellites are located on three orbit planes with an inclination of 55 degrees. The latitude of MEO satellites is 21500 kilometers while it is 36000 kilometers for IGSO satellites.

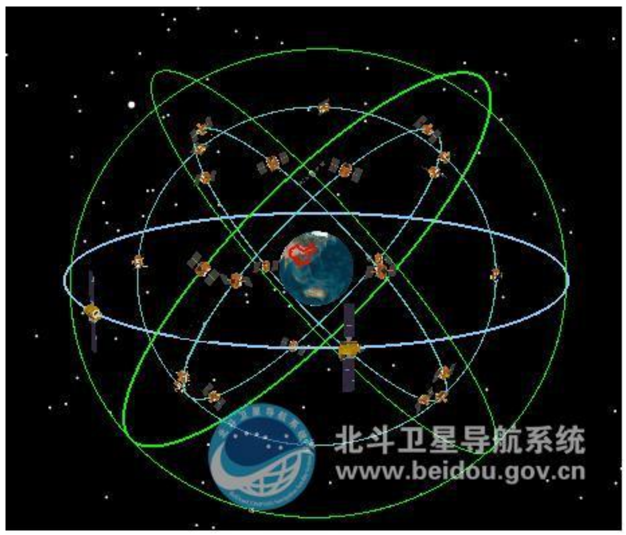

Figure 9. *The final Compass Navigation Satellite System [8]*

The Geostationary Earth Orbit (GEO) describes a circular orbit which is positioned 35,786 kilometers above the Earth's equator and has the same rotation direction with the Earth. The orbit in question is following the Earth's rotation all the time and for that reason they share the same rotational period. To the ground observers, the orbit appears in the sky as a motionless object with a fixed position. Most commercial satellites used for communication purposes, broadcast satellites as well as augmentation system satellites operate in a geostationary earth orbit so that their antennas are constantly being locked at the satellites' position without the necessity of rotating for tracking them down.

A Geostationary Earth Orbit can only be obtained when it is very close to 35,786 kilometers above the earth and directly above the equator at the same time. This equals to an orbital velocity of 3.07 Km/s or an orbital period of 1,436 minutes; simply put that's

23 hours, 56 minutes and 4.0916 seconds. This ensures that the rotational period of the satellite matches the one of the earth's and leaves a static trail on the ground. Every geostationary satellite mush stay on this ring.

Figure 10 and 11 below represent settings and an example of the Compass satellites on the sky, visible from Tampere Finland as set in the settings. The plots are based on Microsoft Silverlight which is an online tool to discover different GNSS systems. Figure 10 shows the settings of the location, date and time span while figure 11 gives the visible Compass satellites based on the settings.

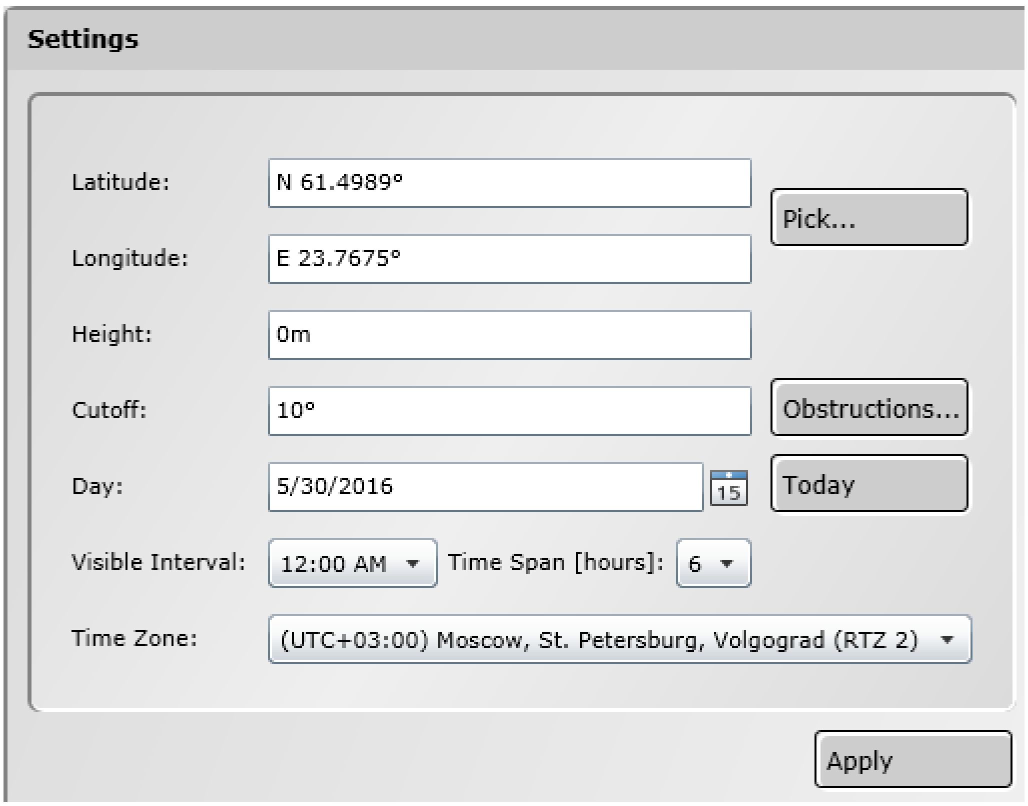

Figure 10. *Settings in Microsoft Silverlight*

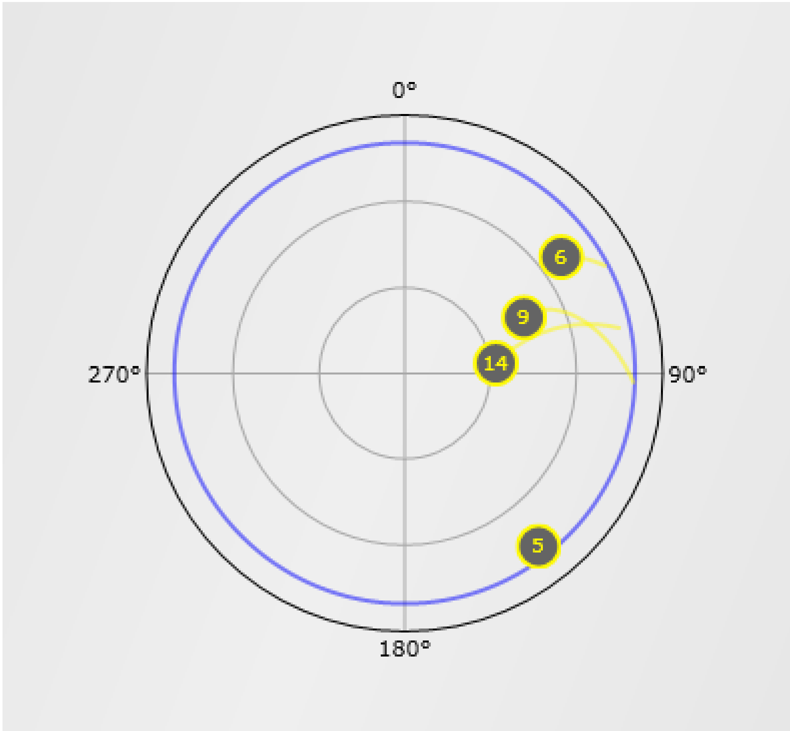

Figure 11. *Visible Compass satellites on sky with a 6-hour span*

One thing that needs to be taken into consideration is the orbital perturbation which basically means the complex motion of a massive body subject to forces other than the gravitational attraction of a single other massive body [9]. The combination of lunar and solar gravity as well as the earth's flattening, result in a precession motion of any geostationary orbit of the orbital plane. It has an orbital cycle of almost 53 years and approximately 0.85 degrees of initial inclination gradient per year which produce 15 degrees of inclination after 26.5 years. In order to correct this, regular orbital station-keeping maneuvers are needed. The orbital station-keeping is the use of any methods to accelerate the artificial satellites to change the orbit of a spacecraft. For Geostationary Earth Orbit, this accelerate is approximately 50 m/s per year.

Since the equator of the earth is considered elliptical, it means that the earth is not 100% round and yet another aspect to consider is the longitude drift. There are two stable equilibrium points at 75.3 degrees east and 104.7 degrees west as well as two unstable equilibrium points at 165.3 degrees east and 14.7 degrees west. Any geostationary object traveling between these points will have a slow acceleration towards the stable equilibrium position which will result in a periodic longitude variation. Once again, the station-keeping maneuvers correct this drift by around 2 m/s per year.

Since the Geostationary Earth Orbits are positioned significantly far away from the earth, there is significant latency from the orbits to the earth. The latency is around 0.25 seconds for a trip from one ground-based transmitter to the satellite and back to another ground-based transmitter; it has approximately 0.5 seconds of latency for a round trip from one Earth station to another and back.

Geostationary satellites are positioned just above the equator and are placed lower in the north or south. Because of the refraction in the atmosphere, the thermal emission of the earth, the line-of-sight obstructions as well as the ground signal reflections or nearby buildings, the communication between the satellites and the observers on the ground becomes more and more difficult while the observer's latitude increases. For latitudes that are above 81 degrees, the Geostationary Earth Orbits are below the horizon and totally cannot be seen.

Since all the Geostationary Earth Orbits are located on the same height above the earth's equator, it means that all the orbits occupy a single ring in the sky. Thus, how to separate and distinguish all these satellites is a crucial question. The reason to keep these orbits separated is to avoid any harmful and unnecessary interference during radio frequency transmissions and operations. This means that there is a limited number of positions available for the orbits and only a limited number of satellites can be operated in geostationary orbit. For countries with different latitudes but all near the same longitude, there will be conflicts since all countries want to get access to the same orbital 'rooms' and radio frequency. The international telecommunication union set the allocation mechanism rules.

Medium Earth Orbit is encompasses all orbits between 2,000 kilometers above the Earth and 35,786 kilometers above the Earth. MEOs are frequently used for navigation, communication and geodetic environment science. The most common altitude is about 20,200 kilometers which result in an orbital period of 12 hours, as used by GPS. As discussed in the previous chapter, navigation systems such as GPS, Glonass and Galileo all have the satellites placed on MEO orbits. Communications satellites that cover the North and South Pole are also put in Medium Earth Orbit. The orbital periods of Medium Earth Orbit satellites range from about 2 to 12 hours. Some MEO satellites have constant altitude and travel at a constant speed because they are travelling in almost perfect circles.

If there is an angle other than zero degrees between the earth equatorial plane and the orbit, this kind of satellite is considered an inclined orbit around the earth. The angle is known as the orbit's inclination. One special case of inclined orbit is the Inclined Geosynchronous Orbit. As introduced before, a geostationary orbit is a satellite that is a circular orbit which located 35,786 kilometers above the equator of the Earth and has the same rotation course with the Earth. Since it is following the rotation of the Earth all the time, it has the same rotational period with the Earth as well as appears to the ground observers as a motionless, fixed position in the sky. A satellite is considered an inclined orbit when its orbital plane forms an angle with some number of degrees from the earth equatorial plane. Thus, for an Inclined Geosynchronous Orbit, the satellite will remain geosynchronous which means the time for completing one orbit round the earth is approximately 23 hours 56 minutes and 4.9 seconds. However, it is no longer geostationary. If observing from a fixed point on the earth, the orbit would appear to trace out a small ellipse as the influence of gravitational effects of other stellar bodies over the satellite. As the influence accumulates over time, the trace finally becomes an analemma with lobes oriented north-southward [10].

Table 5 below represents the satellites that are currently being used for the Compass Navigation Satellite System. The table shows different satellites and their types (GEO or MEO or IGSO) with the longitude they are working at as well as the date they were launched. Until April 2016, a total of 26 satellites had already been launched with the latest one on 30th of March, 2016. However, BeiDou-G2 (the second GEO being launched) is now drifting which means it is out of control and it cannot provide any kind of service anymore. Meanwhile, the BeiDou-M1 (the first MEO launched) satellite was diagnosed with defected components which resulted in repeated timing issues. At present (as of April 2016), among all the satellites that had been launched, 16 of them are fully operational with the other two, which was just launched in 2016, currently in commissioning status. BeiDou-1A, BeiDou-1B, BeiDou-1C and BeiDou-1D which are known as the first generation of BeiDou system are retired between 2009 and 2012 whose main purpose was for experiments. In addition, Compass-M1 and Compass-G2 which was launched in 2007 and 2009 respectively were also not in use any more.

Table 6. *Satellites of current Compass Navigation Satellite System*

Satellite	Status	Operational Orbit	Launching Date
Compass-G1(GEO)	Working	140 ºE, Height 35807Km, inclination 1.6º	2010.01.17
Compass-G2	Failure	Height36027Km, inclination 2.2º	2009.04.15
Compass-G3(GEO)	Working	110.6ºE, Height 35809Km, inclination 1.3º	2010.06.02

Compass-G4(GEO)	Working	160 ºE, Height 35815Km, inclination 0.6º	2010.11.01
Compass-G5(GEO)	Working	58.7 ºE, Height 35801Km, inclination 1.4º	2012.02.25
Compass-G6(GEO)	Working	80.2 ºE, Height 35803Km, inclination 1.7º	2012.10.25
Compass-I1(IGSO)	Working	Height35916Km, inclination 54.6º	2010.08.01
Compass-I2(IGSO)	Working	Height35883Km, inclination 54.8º	2010.12.18
Compass-I3(IGSO)	Working	Height35911Km, inclination 55.9º	2011.04.10
Compass-I4(IGSO)	Working	Height35879Km, inclination 54.9º	2011.07.27
Compass-I5(IGSO)	Working	Height35880Km, inclination 54.9º	2011.12.02
Compass-I6(IGSO)	In Commissioning	Inclination 55 º	2016.03.30
Compass-M1(MEO)	Working	Height21559Km, inclination 56.8º	2007.04.14
Compass-M3(MEO)	Working	Height21607Km, inclination 55.3º	2012.04.30
Compass-M4(MEO)	Working	Height21617Km, inclination 55.2º	2012.04.30
Compass-M5(MEO)	Working	Height21597Km, inclination 55.0º	2012.09.19
Compass-M6(MEO)	Working	Height21576Km, inclination 55.1º	2012.09.19
BDS I1-S(IGSO)	Working	Inclination 55.0º	2015.03.30
BDS I2-S(IGSO)	Working	Inclination 55.0º	2015.09.29
BDS M1-S(MEO)	Working	MEO – 21,500Km	2015.07.25
BDS M2-S(MEO)	Working	MEO – 21,500Km	2015.07.25
BDS M3-S(MEO)	In Commissioning	MEO – 21,500Km	2016.02.01

According to the “Three-step” plan, China is still in the process of launching another batch of satellites in an attempt to turn the current Compass Navigation Satellite System into a system with higher precision, reliable and robust positioning providing improved navigation and timing services at a global scale.

Figure 12 below represents an example of how the Dilution of Precision (DOP) varies for through time with the same settings in Figure 10. Any DOP figure that is lower than 5 is considered a good value which means the navigation carried out is highly reliable. In Figure 12, GDOP, TDOP, PDOP, VDOP and HDOP are all displayed. They are all different types of DOP. More details and GDOP comparisons with other GNSS systems can be found in “Multi-GNSS analysis via Spectracom constellations”. [43]

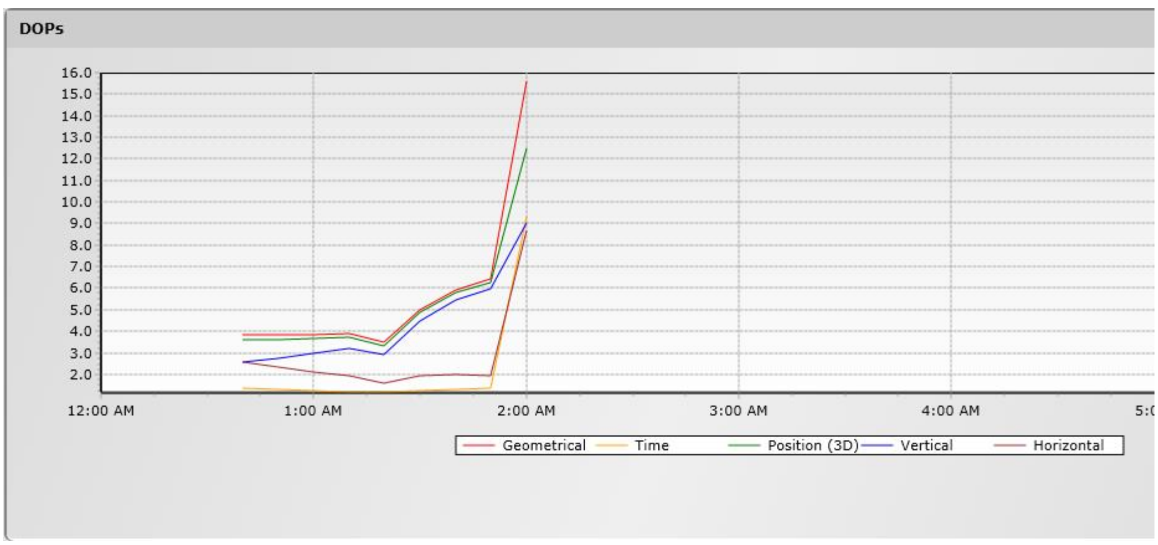

Figure 12. *Example of DOP fluctuations for Compass*

4.2 Compass Ground Segment

The Compass ground segment of the Compass Navigation Satellite system is composed of the master control, the injection and monitor stations.

The primary functionality of the master control station is to process and analyze the data collected from all the monitor stations and to maintain the satellite navigation message and information about the differential integrity. As the name of this station defines, it is responsible for managing and controlling the entire system. The master control station of Compass Navigation Satellite System is located in Beijing, China.

The injection stations control and manage the injection of the satellite navigation message and process information about the differential integrity produced by the master control stations as well as the effective payload. China is planning to construct three injection stations which will be located in Beijing, Kashgar and Sanya – one in each site.

As already mentioned in previous chapters, the monitor stations tend to receive signals from the satellites and forward those signals to the master control stations in an effort to track and monitor the satellites effectively. In addition, they provide important information about determining the orbit of the satellite and the synchronization of time. China will first implement and deploy the monitor stations within its national borders before expanding towards the whole world.

Figure 13 below represents a satellite antenna which is part of the monitor stations. The type of this antenna is metal parabolic with high directivity which basically means it is responsible for directing the satellite signals at specific locations. It absorbs the weaker attenuated signals generated by the satellite and removes the noise as much as possible.
This kind of antenna is known as a satellite dish. It defines a dish-shaped parabolic antenna aimed at receiving electromagnetic signals from the satellites which transmit or broadcast data. A parabolic antenna on the other hand, is another type of antenna which uses a parabolic reflector, has a rather curved surface with the cross-sectional shape of a parabola, to direct the radio waves [11]. The major benefit of a parabolic antenna is that it has a high directivity. In addition, it provides the highest gains and adjusted as such to produce the most narrow beam widths of all the other antenna types.

The principle of operation of a dish-shaped parabolic antenna is shortly explained here. The parabolic shape of the antenna allows easier reflection of the signal to the dish's focal point. The device which is mounted on the brackets of the dish's focal point is commonly known as a feed horn. The feed horn is a very important component of the front-end because it gathers all the direct or indirect inbound signals targeting the focal point and 'transfers' them into a low-noise block downconverter (LNB). The LNB is responsible for converting the signals from electromagnetic or radio waves to electrical signals as well as shift the signals from the downlinked C-band and/or K_u-band to the L-band range. C-band defines the electromagnetic spectrum, including the wavelengths of microwaves which are used for long-distance radio telecommunications. K_u-band is the 12-18 GHz part of the electromagnetic spectrum in the microwave range of frequency [12]. L-band is the 1-2 GHz range of the radio spectrum.

Figure 13. *Satellite Antenna [13]*

4.3 Compass User Segment

The user segment of the Compass refers to any terminals that are able to receive the Compass' radio signals and use that information to perform complex calculations in regards to the coordinates.

Compass has a huge variety of applications, in different areas. For example, in military uses, the Compass assists in planes' navigation, missiles guiding and direction as well as other military devices. In this way devices are able to determine their own location, while being centrally controlled from a remote location.

In addition to military applications, Compass also provides a variety of services for the individuals and the public. The most popular service people are using today is the navigation application on their cellphones. With a cellphone that has a chipset that can receive Compass radio signals inside, the location can be easily found with Compass system. Meanwhile, Compass also assists weather monitoring. With the development of Compass, it is easier and more accurate to monitor the weather changes in order to prevent major natural disasters.

The Compass Navigation Satellite System provides two types of services, an open service and an authorized service. The open service's primary objective is to provide an open, stable and reliable position as well as velocity and timing services to all people all over the world free of charge. The target accuracy of positioning is 10 meters, 0.2 meters per second for velocity and 10 nanoseconds for timing. Nevertheless, the authorized service offers higher performance in positioning, velocity and timing services which are supposed to reach the centimeter-level when fully implemented. In addition, this service also provides a wider area of differential global positioning and short message communication services within the APAC region. The accuracy of the wide area differential global positioning is 1 meter. BeiDou-2 is not only a simple extension of BeiDou-1, but it is also designed as such to improve and correct a number of its disadvantages.

Thus, it is important to have a general idea about what is Compass receiver. Just as all the other GNSS receivers, the Compass receiver constitutes of the front-end, acquisition block, tracking block and navigation block.

4.3.1 Receiver Front-End

The front-end is where the source of the data stream is being processed. The satellite signals need to be propagated into multiple digital data streams in order to be further analyzed and processed. Figure 14 provided below gives a brief introduction of how a front-end looks like. It is generally composed of an antenna, a number of filters, an amplifier, an oscillator, and an analog-to-digital converter. The antenna is how the satellite signals are being received and in most cases these are rooftop cables. The filters, in this case Bandpass filters, are frequency selective devices that allow only specific frequencies to go through and attenuate the rest accordingly. Since the antenna passes signals from all the frequency bands, filters are essential to only gather the signals that are needed while eliminating any unnecessary signals from the stream. The amplifier is used to increase the magnitude of the signals and maintain the signal's quality by reducing the noise in such a way so that the weak signal can be identified by the analog-to-digital converter. The purpose of the oscillator is to translate the higher radio frequency into lower intermediate levels while preserving the modulated signal structure. In addition, the oscillator plays a dramatic role by increasing the quality and lowering the cost of the electronic components, reducing the shielding levels as well as decreasing the feedback potential from the lower frequency to the higher frequency amplifier. The electronic components are generally crystal oscillator which cannot generate the local oscillator frequencies so that a phase lock loop is combined to achieve the desired frequency. Also, a division can be made to the output of the PLL in order to serve as the sampling clock. Last but not least, as the name defines, the analog-to-digital converter is used to convert the signal from its analog format to a digital format ensuring that the signal can be processed within the software receiver.

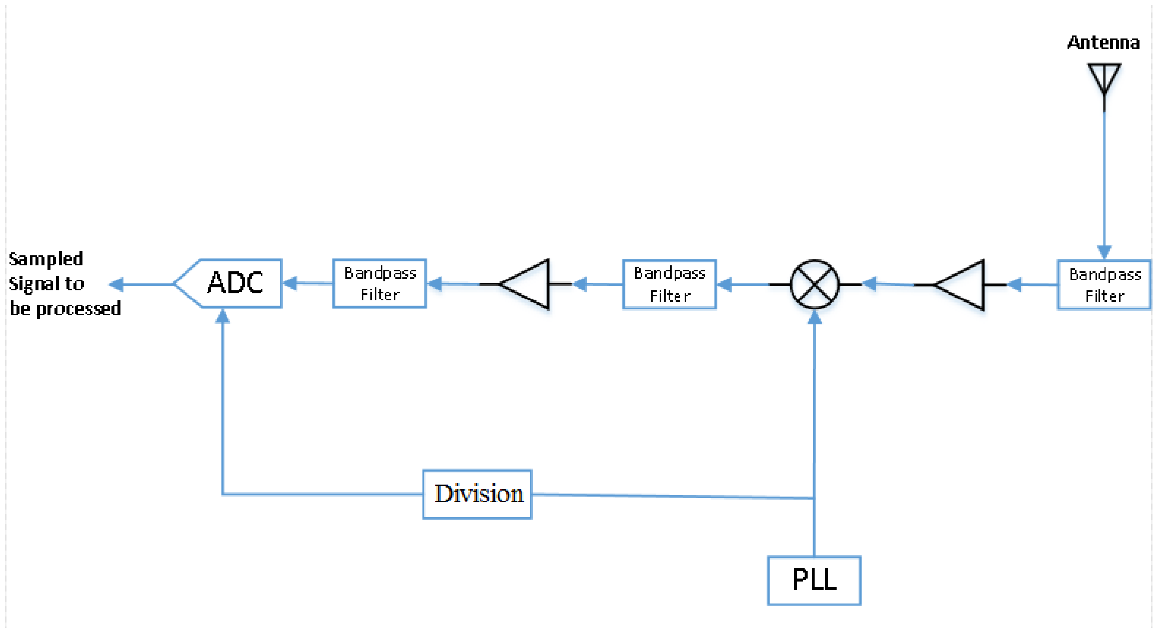

Figure 14. *Compass Receiver Front-end*

4.3.1.1 Compass/GNSS Antenna

Generally speaking, the antenna is not part of the design for the front-end. However, it is very important to have a general idea about this device when analyzing the front-end since it is an element of the signal path as well as it influences several factors in the receiver chain.

On October 19th, 2015, China Compass Satellite Standardization Committee released the performance requirements and test methods for compass navigation antenna. This standard defines the performance requirements of compass circularly polarized passive antenna and active antenna as well as their test method. It is also a reference for developing, producing and testing navigation antenna installed on any vehicles, ships and mobile terminals. [33]

The most general rule of a compass navigation antenna is at least able to receive the open service signal broadcasting by compass navigation satellite system as well as receive signals from other GNSS systems. The recommended output impedance is 50Ω while the output connection mode is decided by the manufacture or user but has to be illustrated in the product specification. In addition, from the manufacture point of view, the antenna surface should be bright and clean without any dent, scratch, crack, deformation and other kinds of blemish. The surface of any metal should be cover with a rust-proof and anti-corrosion layer. [33]

Consider a passive antenna, which is the kind of antenna that does not have any amplification circuit and is able to work without any additional power supply, this standard gives the value of several antenna parameters which is shown in the following table:

Table 7. *Compass Receiver Antenna Parameters*

Parameter	Value
VSWR	No more than 3.0
Polarization and Axial ratio	Right handed circular polarization. Axial ratio should be less than 15dB.
Normal polarization gain	Not less than -3 dBic
Front-to-rear ratio	Not less than 3.0 dB
Out-of-roundness at 20 degrees elevation	No more than 5.0 dB
Average gain at 20 degrees elevation	Not less than -10.0 dBic

Voltage Standing Wave Ratio, which known as VSWR in short, is a function of frequency and also a measurement relation, expressing the amount of incident power absorbed as well as the amount that will be reflected. It is a numerical measurement of how well the impedance matches to the transmission line it is connected to. The ideal ratio would be 1.0 which means no power is reflected from the antenna, the bigger the ratio, the worse the impedance matched to the transmission line and the less power is delivered to the antenna. As of the value defined by this compass standard, the VSWR should not be more than 3.0 within desired frequency band which indicate that at least 75% of power should not be reflected and delivered to the antenna. One thing to note is that by VSWR itself, it is insufficient to determine whether an antenna is functioning properly or not. The reason is that VSWR only describes how much power can be delivered to the antenna but not necessarily means that all the power delivered can be radiated by the antenna. Thus, more tests regarding radiation may need to be carried out.

The Compass navigation antenna should be designed to be right-hand circularly polarized (RHCP). Polarization indicates the direction of the electric field during the transmission of radio frequency. Circular polarization, in electrodynamics, means that the magnitude of the electric field vector, which defines an electric field, stays constant while the direction is changing in a rotary manner. The simplest way to understand circular polarization is to divide the electric field into one vertical and one horizontal plane. From the receiver's point of view, if the rightward horizontal plane leads the vertical plane by one quarter of a wavelength, this is considered a right-hand circular polarization (clockwise). The use of RHCP is not decided randomly. The most complicated issue with GNSS is the multipath issue. During the journey of the signal from the source to the receiver, it may be reflected by different objects such as buildings and cars as well as ionosphere which results in the receiver receives signals from two or more paths. This is the so-called multipath phenomenon. A situation that is not desired to happen when measuring the time of reception is that GNSS signal may suffer reflections on the ground and they result in left-hand circularly polarized (LHCP) signals. For this issue, RHCP is able to suppress LHCP reflection and minimize this error source. Certainly, if the signal reflects again, it will come back to RHCP, however, the signal power will decrease because of multiple times of reflections. Thus, polarization is necessary to minimize the error caused by multipath reflections.

The axial ratio is expressed as the ratio between the two orthogonal components of an electric field. Ideally, those two components should have the same magnitude which results in the axial ratio to be 1 (0 dB), nevertheless, the further away it is from the direction of maximum radiation, the larger the axial ratio. As defined in compass standard, this value should not exceed 15 dB.

The gain pattern defines the directivity of the antenna. The main concept of the gain pattern is to receive the signals equally from all possible directions which can be easily achieved with the use of an isotropic antenna. Unfortunately, this type of uniform gain pattern cannot by applied for GNSS. Since most GNSS signals precede the receiving applications, the ideal antenna pattern would be hemispherical in order to get the signals from all azimuth directions and from only positive elevation angles. Because of the multipath issue discussed above as well as the fact that most of the multipath signals are being delivered with low elevation angles, the antenna should be designed accordingly to only receive the signals whose elevation angle is more than 20 degrees. With this kind of design, the influence of multipath will be decreased, but meanwhile, the signals with low elevation angles will be eliminated which reduces the availability of satellite measurements. For Compass, as defined in the standard refers to [33], at 20 degrees elevation, the maximum fluctuation of the antenna gain should be less or equal to 5.0 dB while the average antenna gain should not be less than -10.0 dBic.

Normal polarization gain is the power density ratio between the designed antenna and the isotropic circular polarization antenna in normal direction under the same input power. For Compass, this parameter should be more than -3 dBic.

The front-to-rear ratio of a compass navigation satellite should not be less than 3.0 dB as defined in the referred standard [33]. This means the ratio between the maximum gain at a specific direction with the gain of the opposite direction (180 degree) of the antenna should be larger than 3.0 dB otherwise the antenna is not good enough to reject the signal coming from rear.

Consider an active antenna, all the parameters of the passive part within the active antenna remain the same as above except VSWR which should be no more than 2.0 which means only around 10% of power is reflected across the bandwidth of the desired frequencies.. In addition, three more aspects need to be taken into consideration.

One of the most important parameters when designing the front-end is the overall noise figure F_n. It defines the noise added by the analog signal conditioning. It is apparent that any type of additive noise or decrease in signal-to-noise ratio (SNR) is unwanted and should be reduced as much as possible.

Assume that the system noise symbol is represented by F_{system}, the noise figure of the n^{th}element in cascade by F_n and G_n describes the gain of the n^{th}element in cascade. The formula for noise figure is then constructed as follows [44]:

$$F_{system} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \cdots + \frac{F_n - 1}{G_1 G_2 G_3 \dots G_{n-1}}$$

From the formula, it is evident that the initial element found in the cascade dominates the entire system noise figure in the front-end. This basically means, that all the inactive components, such as cables, filters, will have negative influence to the noise figure. Similarly, the component will have a minimal influence to the overall noise figure, after a high gain amplifier.

For example, taking into account that a GNSS receiver is being used in a housed controlled environment, and the best place for the GNSS antenna is the roof top since there are no obstructions. However, under most circumstances, a very long cable is needed in order to connect the antenna to the laboratory. The RF cable which connects the antenna and the front-end is the first element in the cascade. As all the RF cables share a fair amount of attenuation or noise figure without gain, the system noise figure will be highly affected. However, if the amplifier is incorporated in the antenna before the cable, the situation will be significantly improved. This kind of implementation is very frequent in GNSS antenna which is known as active antenna whose characteristics can be described with the gain of the amplifier. For Compass, as defined in the standard [33], the noise figure should not be more than 2.0 dB.

It is quite more complicated with an active antenna since the antenna itself is already considered as an active element where the amplifier found inside needs power supply. In order to achieve the incorporation of amplifier with the antenna, a bias-tee is used in most cases. The bias-tee is a three ports circuit consists of capacitor and coil. Ideally, the capacitor would block direct current bias and allow only alternating current while the coil would block alternating current and allow only direct current. It contains three ports: RF, RF+DC and DC. These three ports are often formed a T-shape so that the name of ‘tee’ is given to this circuit. This component feeds DC power to the antenna from the front-end and provides the power supply needed to the amplifier inside. Thus, the antenna cable not only transmits the GNSS signal from the antenna to the analog signal conditioning part, but also feeds the bias voltage to the amplifier.

The working voltage of an active antenna should fall between 3VDC to 5VDC with current smaller than 20mA. Low noise amplifier, as it is named, is a kind of amplifier that enlarges a very low-power signal while minimize the additional noise in order to achieve a relatively higher SNR. Except VSWR, the values of the other three parameters can be varied from antenna to antenna and should be defined in the product specification.

4.3.1.2 Filter Stage

The first component that the RF signal is going through is the filter. The filter is a frequency selective component, which only allows RF signals that are under specific frequencies to go through and attenuate the signals found under any other frequency range.

The BPF in Figure 15 is a Band Pass Filter, it provides additional frequency selective functions. Ideally, the antenna should only receive the voltage from the desired frequency band. However, practically nothing is ideal. The ideal filter will allow all the signal within certain frequency range pass and eliminate all the other signals within other frequency band. This kind of ideal filter does not exist. The transition between the passed and eliminated signals is gradually. Moreover, even the signal within the passing bandwidth will still be attenuated somehow.

A typical antenna has a very bad frequency selective function. It is very important to consider all the aspects such as the received signal power levels, the frequency selectivity the required amplification, and then eliminate any high-power, out-of-band signal sources that could enter the front end and cause saturation to the components later on. Based on these aspects above, the first component found after the antenna is generally a band pass filter.

One drawback of filter is that it also causes insertion loss or attenuations to the desired frequency component. Ideally, there should not be any kind of loss or attenuations, however it cannot be implemented in practical case, thus, the loss should be as small as possible. When the filter is placed before the first amplifier, the insertion loss will have negative influence to the overall system noise figure. However, in order to minimize any issues from the adjacent frequency bands given the limited selectivity of the antenna itself. If the receiver detects that there is no high-power adjacent frequency, then there is no need for the first filter or the position of the first filter and the amplifier can be exchanged. A low insertion loss filter can also minimize the influence to the overall noise figure.

Another parameter of the filter is the bandwidth. Again, since nothing is ideal, 3dB bandwidth is considered to be a typical bandwidth. This describes at which frequency the attenuation will be 3dB (or 50% of the signal power). These two parameters mentioned cannot be fully applied for most filters but can only provide some information regarding their performance.

The band pass filter is shown in the following figure 15. The bandwidth of the filter is the difference between the upper and lower cutoff frequencies $f_H$and f_L. It is measured at half-power points (gain -3dB).

Generally speaking, the main idea for designing a filter is to provide a sharp cutoff between the desired pass-band and the undesired cutoff frequencies for maintaining a minimal insertion loss.

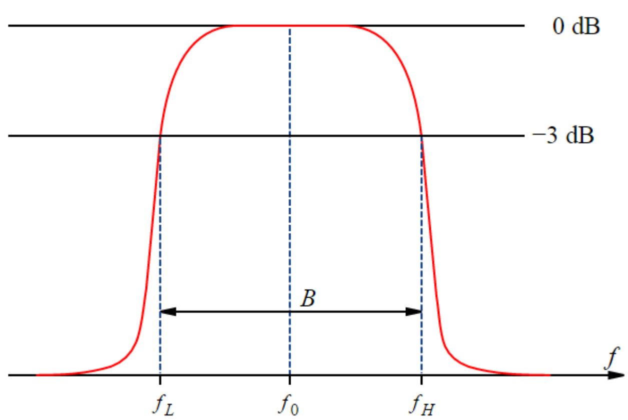

Figure 15. *Band Pass Filter [15]*

4.3.1.3 Amplifier Stage

Amplify defines the process of enlarging a signal and the amplifier itself is the component for achieving this particular process. Unlike most filters, the amplifier is an active component which means that it needs a power supply to operate properly. One thing that needs to be taken into consideration is that the ideal amplifier is only and solely responsible for amplifying the amplitude of the signal. However, any type of amplifier is usually not only able to increase the amplitude of the signal, but also the amplitude of the noise figure within the signal. Thus, the amplifier amplifies the signal as well as introduces as less noise as possible is required.

There are the three fundamental parameters of an amplifier. First is the gain which usually expressed in dB and it is a constant number within certain frequency range. The next one is the certain frequency range and the last one is the noise figure. Again, the noise figure is measured in dB in order to express the noise added when amplifying the signal.

Please note that the discussion here about the amplifier is rather simplified. The amplifier is assumed as a packaged device which tends to ignore the actual fabrication. Moreover, in order to further streamline the discussion, parameters such as the third-order interception point, the power requirements and the maximum power management are not thoroughly discussed.

The main purpose of the amplifier is to increase the weaker signals to a level that can be properly processed by the analog-to-digital conversion bulk. Therefore, the level of amplification is really dependable on the specific ADC.

4.3.1.4 Oscillator

The fundamental function of the oscillator is to convert the input RF to a minor intermediate frequency (IF) while maintaining the construction of the modulated signal. The main reason for doing so is to convert the frequency to a more reasonable range so that it is easier to process the signal especially for analog-to-digital converter.

Typically, the oscillator of the front-end consists of different components. Most of the crystal oscillators, either standalone or temperature compensated (for greater stability), are not capable of generating the anticipated local frequency for the GNSS signal. Consequently, the combination of the crystal oscillator and the phase lock loop (PLL) can be used to generate a higher local oscillating frequency.

The function of the oscillator can be expressed by the following formula with ω_1 and ω_2 denote the input RF frequency and a local generated carrier wave respectively:

$$\cos \omega_1 t \cos \omega_2 t = 0.5 \cos((\omega_1 - \omega_2)t) + 0.5 \cos((\omega_1 + \omega_2)t)$$

The design of the oscillator in Figure 8 can also be perceived as a mixing process. For any type of modulation, complex or not, such as a GNSS spreading code or navigation data can be simply expressed with the following:

$$\mathrm{d(t)}\cos \omega_1 t \cos \omega_2 t = \frac{d(t)}{2} \cos((\omega_1 - \omega_2)t) + \frac{d(t)}{2} \cos((\omega_1 + \omega_2)t)$$

Apparently, the output of the mixer will be the total sum and the differences of the frequencies. It is also of great interest here that the difference frequency is the desired intermediate frequency (IF). The total sum of the frequency is just a consequence in this case, in figure 14, the second filter after the mixed is used to remove the sum frequency component.

In figure 14, the band pass filter is used to remove the undesired frequency component. In truth, in order to just remove the sum frequency component, a low pass filter tends to be enough for most cases since the formulas above are sufficient. However, in practice, the parameters of the mixer which include the conversion loss, the isolation, the dynamic range and the intermodulation assist in making the condition far more complicated. In this case the bandpass filter is specifically chosen to further minimize any complications from the intermodulation products that represent the outcome from the mixing. For this simplified discussion, only the straight forward model of the mixer is presented.[14]

From the combination of the local oscillator and mixer, we are able to convert the radio frequency to a much lower intermediate frequency which is a necessary process of the analog-to-digital conversion. However, this is not the only reason why the frequency conversion is so important for the GNSS receiver.

The first and foremost thing is the quality and cost of the component itself. Narrowband typically refers to 2-8MHz. It is quite difficult and complicated to build a narrowband filter at such high frequencies.

If we denote the quality factor of the filter by Q, the center frequency of the filter is f_{center}, the bandwidth of filter is BW and the quality factor Q can be then expressed as:

$Q = {f_{center}}/{BW}$. For example, if we consider that the bandwidth is 3dB and a filter is used to capture the primary lobe of the signal, the Q factor would have an extremely high value of -770. Most commercial filters' fabric tends to establish a minimal bandwidth of 2% of the center frequency though it somehow really depends on the technology being used at the time. The corresponding quality factor Q would be 50 now which is far less than the previous calculated value 770.

For example, by using the formula above $Q = {f_{center}}/{BW}$ at the resulting 47.74MHz of the design in Figure 8, the quality factor Q is 47.74÷2.046 or 23.33 which is a relatively easy implemented filter. Thus, the conversion to an intermediary frequency enables the usage of a much higher frequency selectivity, as well as allows simpler and cheaper components at the same time.

The second reason for frequency conversion is feedback. The level of amplification in the RF chain is rather huge; it is often more than 100 dB. If a trial is placed on a single frequency, the feedback will have a bigger influence on the signal unless a meticulous shielding and a spatial separation across the RF chain is implemented. If a gain which is more than 100 dB is implemented on all the frequencies within 1575.42 MHz, the feedback between each every amplifiers in the RF chain cannot be prevented even though using high quality RF cables. The utilization of multiple stages within a front-end lets the gain to be properly distributed across the whole frequency.

4.3.1.5 Analog-to-Digital Converter

The final component of the front-end is the analog-to-digital converter whose main function is to convert the analog signal. There are a lot of different kinds of analog-to-digital converters in the market with different parameters to choose such as flash ADC, sigma-delta ADC and so on. The parameters discussed here involve the number of bits, the maximum sampling frequency, the analog input bandwidth and the analog input range.

The CDMA characteristics of GNSS signal requires and utilizes a rather small dynamic range from the sampled signal. It is evident, that if one bit sampling is used, the degradation in the processing of signal is less than two dB. If two or more bits sampling is implemented while using the proper quantization, the degradation will be less than one dB. Therefore, when designing a GNSS front end, it is appropriate to use either a hard limiter to obtain a single bit or a commercial analog-to-digital converter taking all or part of the resulting bits of each sample. Relatively, it is also important to know that if multi-bit sampling is utilized, then some form of gain control must be applied in order to perform the suitable quantization.

While using one bit sampling, the penalty is considered to be less than two dB, so why any front-end would still use multi-bit sampling along with the overhead associated with automatic gain control? This is again because the loss stays less than two dB is an ideal scenario. For example, if narrow-band interfere occurs within GNSS L1, then the interference source will severely influence the single bit sampling as well as the processing of GNSS. Thus, though theoretically the penalty of single bit sampling is less than two dB, multi-bit sampling is frequently used in reality.

The maximum sampling frequency rate depends on the bandwidth of the desired signal. If the maximum sampling frequency is 60MHz, the resulting frequency sampling rate is 30MHz maximum. However, if the intermediate frequency is larger than 0-30MHz sampled information signal, a second frequency translation stage is needed to implement the sampling process.

Although the analog-to-digital converter provides an upper limit of sampling frequency to be 30MHz, the input analog signal to the analog-to-digital converter determines which kind of signal can be captured. For example if this value is 300MHz, it means that any frequency component is fed to the analog-to-digital converter up to 300MHz will be aliased according to the sampling theorem.

According to a previous discussion, the function of the last stage filter in the RF chain is rather obvious. It must be a band pass filter which allows only the desired signal to pass through. It is also important to take into account the fact that aliasing does not only exist in the preferred intermediate frequency but also in all other frequencies within the analog input bandwidth of the analog-to-digital converter. Thus, in order to minimize the noise, it is crucial that the filter before the analog-to-digital converter allows only the desired frequencies to pass and attenuates accordingly all the other frequencies within the analog input bandwidth.

Finally, the final parameter to examine of the analog-to-digital converter, is the analog input range. The analog input range indicates how the voltage range will be adjusted for which the quantization will be distributed across. In the event of a minimum analog input range set at 1V to peak with a 50Ω load, a common settings in a radio frequency design, then a 1V signal corresponds to -17dBW. Therefore, it is rather explanatory why the amplification within the RF chain is needed; to deliver the suitable signal levels. The combination of thermal noise and received signal is quite weak so that any type of analog-to-digital converter cannot properly perform the sampling procedure. Hence, the main objective of the amplifier is to increase the received signal levels to exercise the full range of analog-to-digital converter.

The design of the final amplifier in various GNSS front-ends would represent a variable gain with a feedback signal resulting from processing the implementation after the analog-to-digital converter. This procedure is commonly known as an automatic gain control (AGC) and it is implemented in most GNSS receivers. The function of the front end is to obtain all the available bits with the analog-to-digital converter. While observing the sampled data stream, the gain can be decided on the fly. If the gain is insufficient, it can be increased accordingly and if the gain is that high then the outer analog-to-digital converter bins will have an overwhelming number of samples. At that time the gain can be decreased. The auto gain control can be directed by the expected distribution of the sample bins in which the front end is able to try and minimize the narrow band interference.

To summarize, the goal of most components in the front-end is to adjust the voltage occurrence perceived by the antenna for further sampling by the analog-to-digital converter. In order to achieve this, most analog-to-digital converter must have three basic functions: amplification, frequency down-conversion and filtering. These are all part of the preparation for the analog-to-digital conversion which produces the samples to be processed within the software receiver.

The sampled signals will then go through a number of different steps in order to be used to calculate the positioning. These steps are commonly known as data acquisition, tracking and navigation data extraction.

4.3.2 Receiver Baseband

4.3.2.1 Acquisition

Acquisition defines the process of determining all the available satellites in the sky that are visible to the device. There are two factors that could influence the acquisition of Compass signals.

First, there is relative movement between the receiver and the satellite which brings Doppler shifts which means the frequency of the signal is shifted significantly which results in the increase of bit error rate. In order to demodulate the signal correctly, it is necessary to obtain the Doppler frequency. Meanwhile, because of the auto-correlation characteristics of pseudorandom sequence (will be further discussed in chapter 3.4), the pseudo-code phase of the acquired signal must strictly match with the local generated pseudo sequence. The relative difference must not be more than 1 chip, otherwise the signal cannot be demodulated correctly. The phase of Gold code and the carrier frequency are the crucial parameters because they are the ones determine whether the signal can be demodulated correctly or not. Thus, in compass, the acquisition of these two parameters is a two-dimension searching process. [35]

For compass, in each Doppler shift unit, 2046 chips need to be searched. Assume there are in total M units in a Doppler shift, then 2046 × M units need to be searched with the minimum time to be 1ms. [39]

Secondly, the process of signal acquisition is usually considered a two-dimensional process where the identification of the interval of code phase and frequency will influence the speed as well as the accuracy of acquisition. If the interval is too short, the time of acquisition will be long. Conversely, if the interval is the interval is too long, the acquisition accuracy will relatively decrease. Thus, the proper interval of code phase and frequency searching must be selected based on the actual situation for ensuring the stability as well as reliability of the acquisition. [41]

As discussed above, the relative difference between the local generated pseudo sequence and the received signal must not be more than 1 chip, thus, 0.5chip is the common interval that is chosen for correctly demodulating the signal. Similarly, shifting the radio frequency will also have an important influence. Within the Doppler frequency range, a proper interval needs to be found in order to both fast acquire the radio frequency. The commonly used method is to search within the whole Doppler range so that the frequency which is the closest to the radio frequency can be obtained.

The frequency and code phase of the signal can be only determined when the satellite is visible. Within this thesis, for Compass simulation, we have chosen the parallel code phase search algorithm in order to complete the acquisition procedure. The block diagram below illustrates the structure of the parallel code phase search algorithm. The incoming signal is multiplied by a locally generated carrier signal which is executed as such to eliminate the carrier wave of the received signal. The signal multiplication generates the I signal, and then the multiplication with a 90 degree phase-shifted version of the signal generates the Q signal. The I and Q signals are combined accordingly to form a compound input signal to the DFT function. The generated PRN code is transformed into the frequency domain and the result is complex conjugated. The Fourier transformation of the input is multiplied with the Fourier transformation of the PRN code. The result of the multiplication is distorted into the time domain by an inverse Fourier transformation. The absolute value of the output of the inverse Fourier transformation represents the correlation between the input and the PRN code. If a peak exists in the correlation, the index of this peak marks the PRN code phase of the incoming signal. If the threshold previously defined is exceeded and the frequency and the code phase parameters are correct, then the parameters can be handed over to the tracking algorithms.

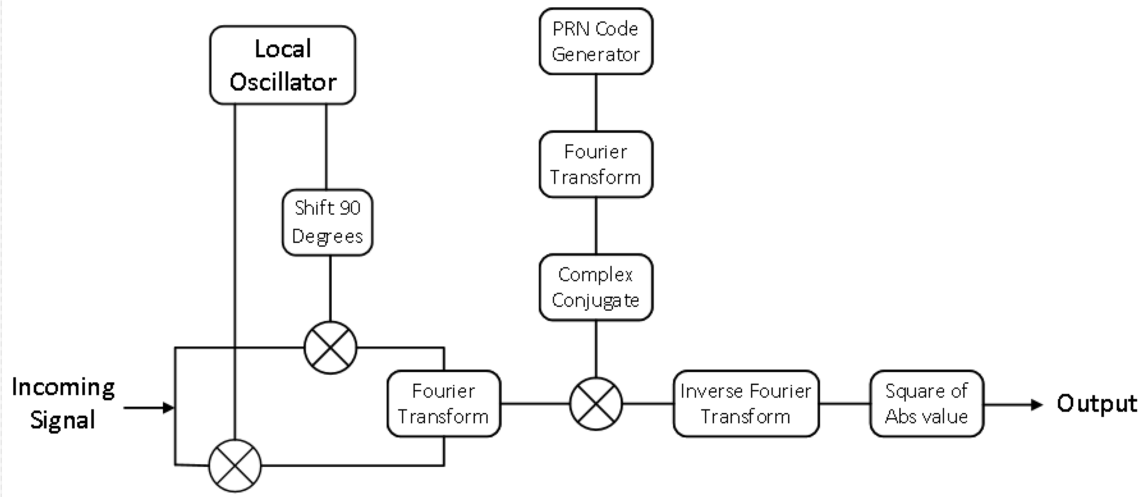

Figure 16. *Parallel Code Phase Search Algorithm*

The acquisition block only provides a coarse estimation of the frequency and code phase measurements. Therefore, the primary objective of tracking is to optimize those values, and maintain the tracking and demodulating procedure of the navigation data received from the visible satellites.

4.3.2.2 Tracking

After the Compass navigation receiver successfully acquires the radio frequency and code phase, the next step is to introduce the tracking process. In the acquisition step, there is a major difference between the acquired and the actual value of the frequency and code phase mainly because of the influence of the Doppler shift as well as the accuracy of the acquisition.

Tracking refines these values, maintains tracking and demodulating of the navigation data from the specific satellite. Figure 17 below briefly represents how the tracking procedure operates. As a first step, the input signal is multiplied with a carrier replica. This is essential and required so that the carrier wave is removed from the signal. During the second step, the signal is then multiplied with a code replica, and the output of this transaction provides the relevant navigation message. Therefore, it is apparent that the tracking process has to produce two replicas, one that will be used for the frequency and another one for the code in order to finely assist in the tracking and demodulation processes of the satellite's signal.

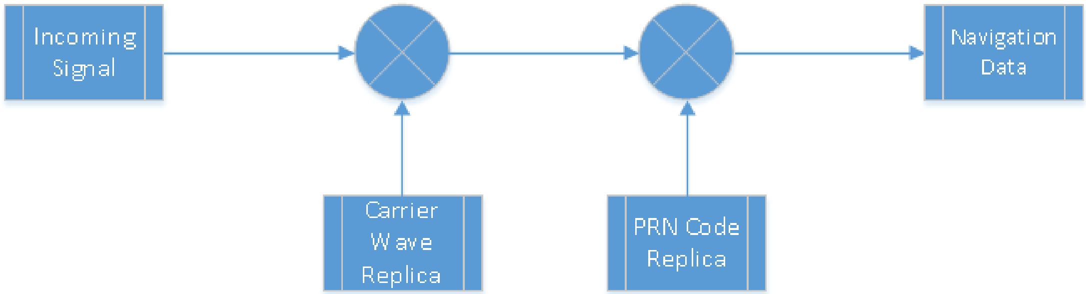

Figure 17. *How the Navigation Data is obtained*

To successfully track a carrier wave signal, a phase lock loop (PLL) or a frequency lock loop (FLL) are most commonly being used. In order to properly demodulate the navigation data received, an exact carrier wave replica must be introduced.

The basic phase lock loop is clearly shown in Figure 18 below. The first two multiplications with the local generated carrier wave and the PRN code remove the carrier and the PRN code of the input signal. The loop discriminator block is practiced in an effort to identify the phase error on the local carrier wave replica. The output of the discriminator defines the phase error and it is then filtered accordingly and fed back to the numerically controlled oscillator. The oscillator then adjusts the frequency of the local carrier wave so that the local carrier wave will represent an almost exact replica of the input signal carrier wave.

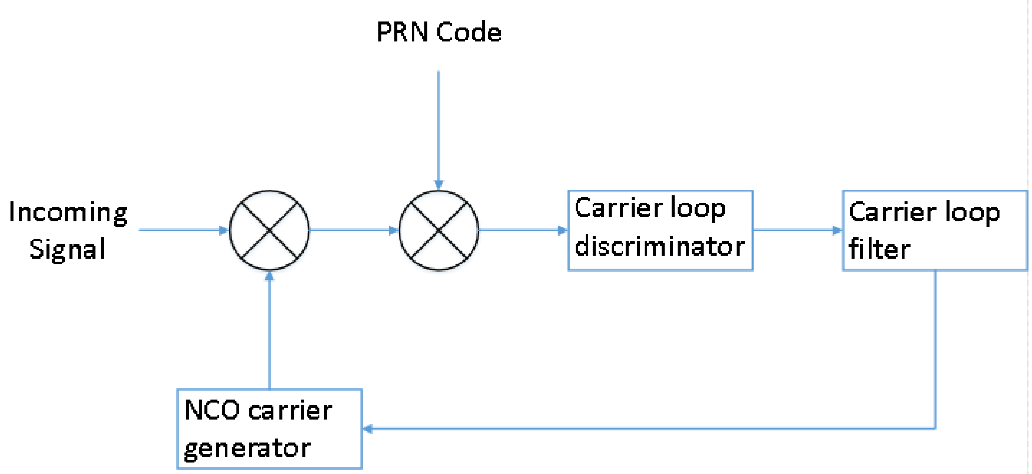

Figure 18. *Basic Phase Lock Loop*

However, there is a big issue with this ordinary PLL which is the fact that it is considered to be sensitive to 180 degree phase shifts. Nevertheless, a PLL applied in a receiver must be insensitive to the 180 degree phase shifts.

Based on the above, Costas Loop is being used for tracking the carrier wave. Figure 19 below provides an example of the Costas Loop. With the multiplication of the PRN code and a carrier generated by the NCO carrier generator, the carrier and PRN code of the input signal are removed. The carrier loop discriminator is responsible for analyze the phase error on the local carrier wave replica and generate the phase error output which is then filtered and used as a feedback to the NCO carrier generator. This procedure adjusts the frequency of the local carrier wave.

The main advantage of using the Costas loop is the fact that it is insensitive for 180 degree phase shifts which basically means it is insensitive for phase transitions due to the navigation bits.

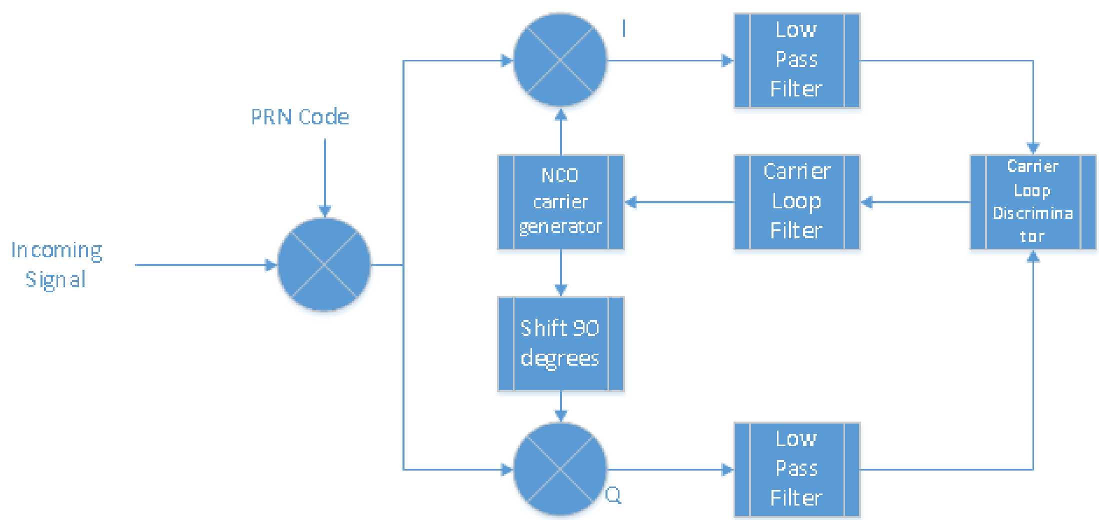

Figure 19. *Costas Loop*

The aim of the Costas loop is to keep all the energy within the in-phase arm. In order to do so, some sort of feedback to the oscillator is required. Considering the code replica is perfectly aligned, the multiplication in the in-phase arm can be expressed as the following, where $D^k(n)$is the navigation data, ω_{IF} is the intermediate frequency to which the front end has down converted the carrier frequency to, φ is the phase difference between the phase of the input signal and the phase of the local replica of the carrier phase.

$$D^k(n)\cos(\omega_{IF}n)\, cos(\omega_{IF}n+\varphi) = 0.5D^k(n)\cos(\varphi) + 0.5D^k(n)\cos(2\omega_{IF}n+\varphi)$$

The multiplication of the quadrature arm can be expressed as:

$$D^k(n)\cos(\omega_{IF}n)\sin(\omega_{IF}n+\varphi) = 0.5D^k(n)\sin\varphi + 0.5D^k(n)\sin(2\omega_{IF}n+\varphi)$$

Since these two signals are then filtered by a low-pass filter, the secondary terms which are with double intermediate frequency are eliminated so that the two signals remain like the below:

$$I^k = 0.5D^k(n)\cos\varphi$$
$$Q^k = 0.5D^k(n)\sin\varphi$$

The phase error of the local carrier phase replica which will be fed back to the carrier phase oscillator can be calculated as follows:

$$\frac{Q^k}{I^k} = \frac{0.5D^k(n)\sin\varphi}{0.5D^k(n)\cos\varphi} = \tan\varphi$$
$$\varphi = \tan^{-1}(\frac{Q^k}{I^k})$$

From the above formula of φ, it is apparent that when the correlation in the quadrature-phase arm is zero and the correlation value in the in-phase arm is at the maximum, the phase error is then minimized. This $\tan^{-1}$ discriminator is the most time-consuming discriminator; however, it is also the most accurate one of the Costas discriminators. There are different kinds of Costas discriminator; table 2 gives the illustration of 3 kinds of them. The output of each discriminator is proportional to different value.

The more intuitive figure which shows the output of each discriminator is illustrated in Figure 20. This figure is drawn with the use of the expressions in table 7 below for all possible phase errors. By comparing the three types of discriminators, it is easy to observe that when the real phase error is either 0 or 180 degrees, the outputs of the discriminators are zero which perfectly verified that the Costas loop is unaffected by the 180 degree phase shifts in case of a navigation bit transition.

Table 8. *Different types of Costas Discriminator*

Discriminator	Description
$D = sign(I^k)Q^k$	The discriminator output is proportional to $\sin\varphi$
$D = I^kQ^k$	The discriminator output is proportional to $\sin 2\varphi$

$D = \tan^{-1}(\frac{Q^k}{I^k})$	The discriminator output is the phase error

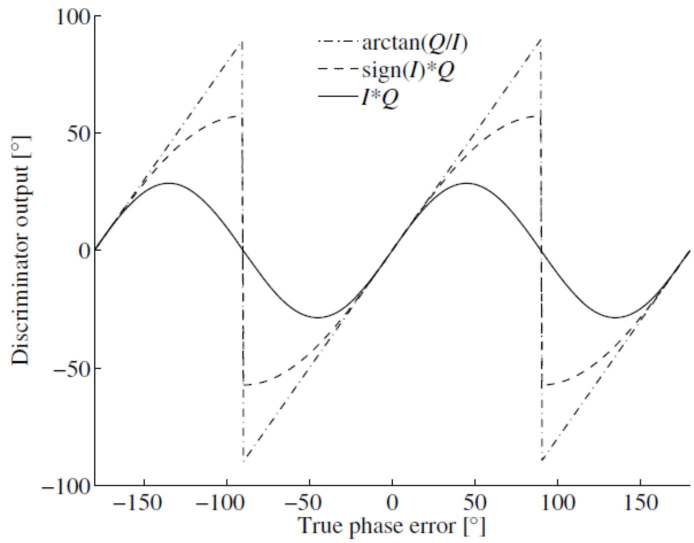

Figure 20. *Outputs of different types of Costas Loop Discriminator [16]*

For the code phase tracking, a delay lock loop (DLL) is used. The DLL with six correlators has the advantage that it is independent of the phase on the local carrier wave. The reason that six correlators are used here is because the incoming signal is divided into in-phase and quadrature arm as well as the local PRN code generator is generating three signals that are some chips away from each other. Not like DLL with three correlators that it is optimal only when the local carrier wave is locked in phase and frequency. The oscillator generates a perfectly aligned local replica of the carrier wave which multiplies with the incoming signal to covert the code to baseband. In addition, another part of the carrier wave generated from the oscillator is shifted 90 degrees in order to catch all the energy in case the local carrier wave is not in phase with the input signal. After this, the in-phase and the quadrature arm signal are multiplied with three replicas which are normally ±0.5 chips away from each other. Finally, the outputs are integrated and dumped to a numerical value indicating how much the specific code replica correlates with the code in the incoming signal.

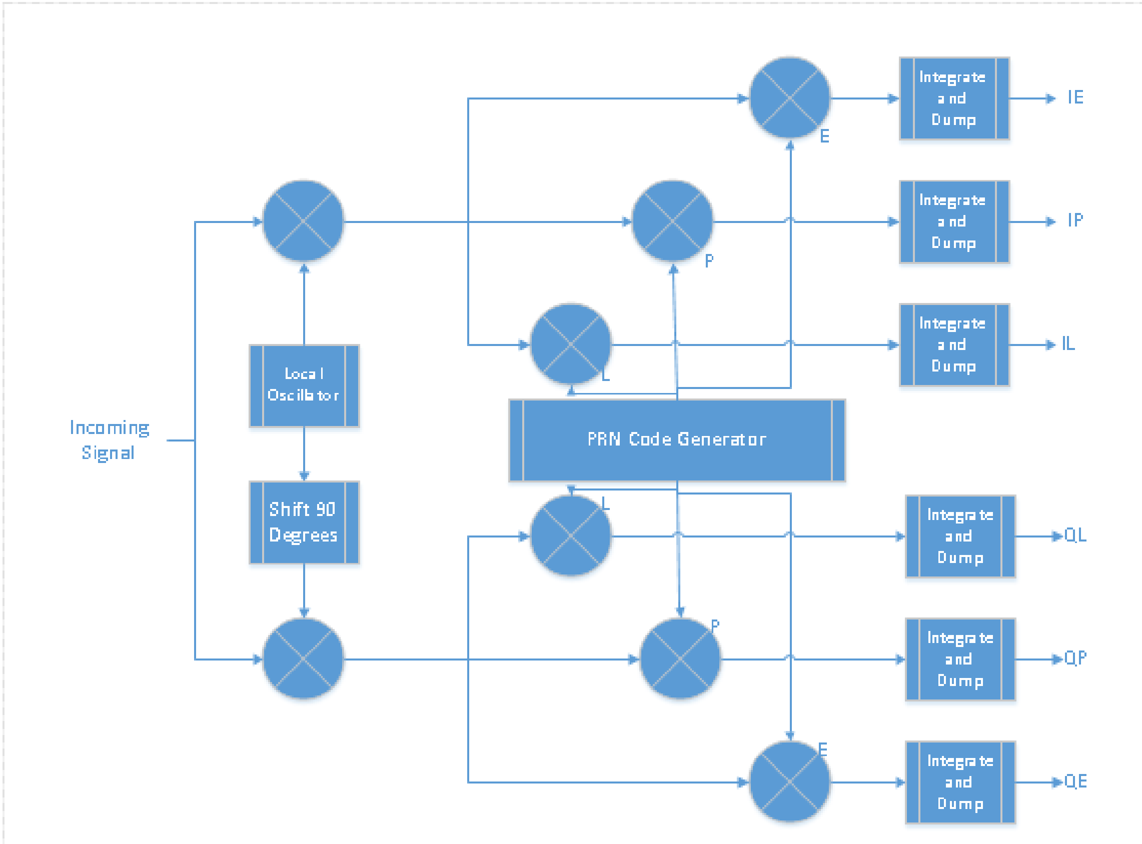

Figure 21. *DLL with six correlators*

In fact, the Costa Loop and the DLL with six correlators can be combined together which forms the structure in Figure 22 below. In this way, the in-phase and quadrature output of the code tracking loop will be the inputs of the code loop discriminator which eliminates the three multiplications in the Costa loop and hereby the computation time is reduced. [37]

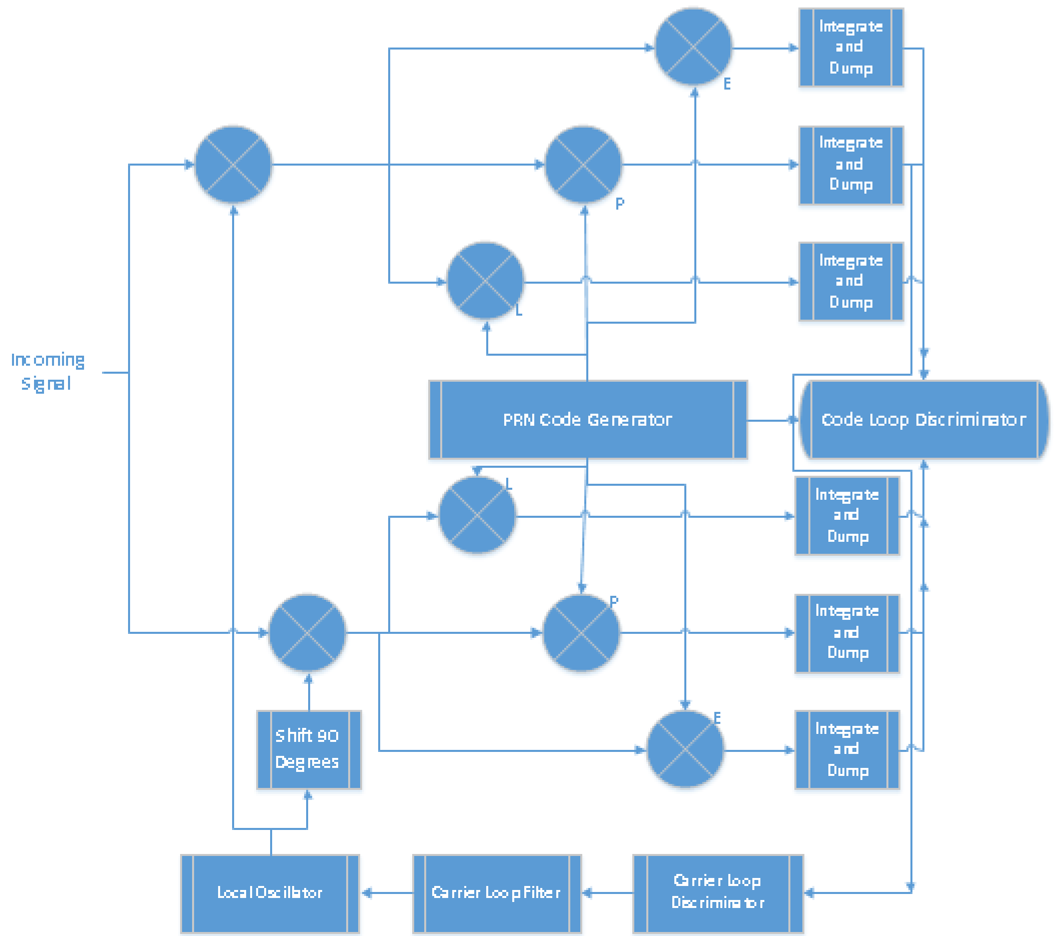

Figure 22. *Complete Tracking Loop*

5 PVT computation and coordinate systems

In this chapter, the procedure and calculation of the position is discussed.

When positioning is mentioned, the first thing to consider is how to properly represent a point on the earth in order to be able to do the following necessary calculations. The earth is not a fixed, rigid sphere, it is basically moving and turning all the time. Thus, in order to compute the distance between the users on the earth and the satellite in the far sky, a relative fixed system is needed. The simplest way is to engage both the users and the satellite into a common coordinate system and to keep the stationary objects to be fixed is crucial.

The Conventional Terrestrial Reference System (CTRS) is an earth-fixed system. It is also known as Earth-Centered, Earth-Fixed (ECEF) system. The fundamental plane contains the earth's center of mass which is known as the origin and it is also pointing perpendicular to the Earth's Conventional Terrestrail Pole (CTP). CTP is an average position of the earth's pole of rotation between 1900 and 1905. The figure illustration of CTRS is as Figure 23 shown. The Z-axis is defined by the Conventional Terrestrial Pole (CTP). The X-axis points to the intersection between the equatorial plane and the mean Greenwich meridian. The equatorial plane, also known as equator, is an imaginary line equidistant from the North Pole and South Pole, dividing the Earth into the Northern Hemisphere and Southern Hemisphere [22]. The Greenwich meridian is also an imaginary line, however, it is used to indicate 0degree longitude that passes through Greenwich and terminates at the North and South Poles. The Y-axis is orthogonal to the above axis in order to form a right-handed coordinate system.

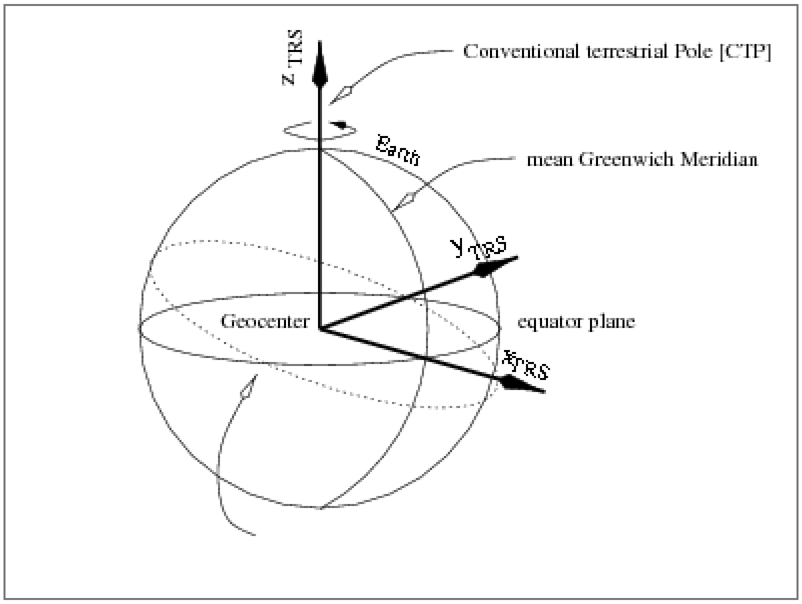

Figure 23. *Conventional Terrestrial Reference System* [23]

The combination of Keplerian orbit elements and Earth-centered and Earth-fixed coordinates X,Y,Z is used.

First, the six Keplerian elements in Figure 24 are very important; they are used to describe the orbit of the satellite which is further illustrated in table 8. Except the parameters in table5, i is the inclination of orbit which means an angle between a reference plane and the orbital plane. In Figure 23, the reference plane is the equator. f is the true anomaly, which defines the position of a body moving along a Keplerian orbit[24]. Perigee, which is the closest point to the earth, is denoted as P and the center of earth is denoted as C. K is the ascending node which is the direction of satellite when it is moving from South to North.

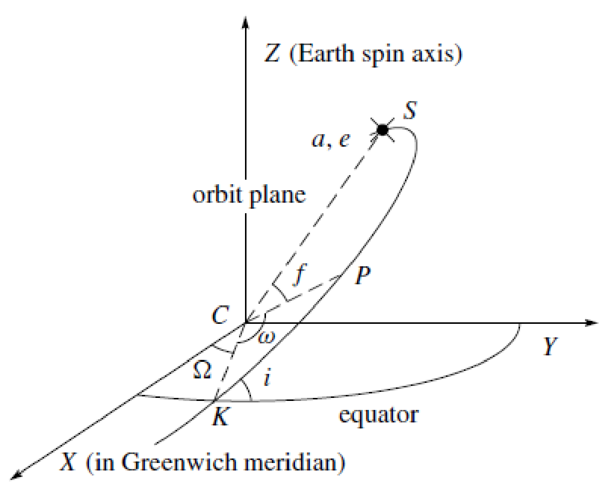

Figure 24. *The Keplerian orbit elements [24]*

Table 9. *Kelplerian Orbit Parameters*

a	*Semi-major axis*	*Size and shape of orbit*
e	*Eccentricity*	
ω	*Argument of perigee*	*The orbital plane*
Ω	*Right ascension of ascending node*	
i	*Inclination*	
μ	*Mean anomaly*	*Position in the plane*

It is not hard to realize that from the above orbit system, the result of the position would be in a (x,y,z) form which is known as Cartesian coordinate. Nevertheless, normally, the position in satellite systems would preferably to be described by (φ,λ,h) - φ is latitude, λ is longitude and h means height, which is known as Ellipsoidal coordinate or Geodetic coordinate.

Figure 25 gives a more visualized impression between these two coordinates. Before getting to the formula and calculation connections between these two coordinates, World Geodetic System 1984, which is WGS 84 in short, needed to be introduced first. WGS 84 was defined and maintained by the United States National Geospatial-Intelligence Agency (NGA) [25]. It is wide used for all positioning applications such as mapping, charting, navigation and so on. WGS 84 also defines several frequently used parameters which are shown in table 9. The semi-major axis is the half of the major axis, which is the longest diameter of an ellipse. Basically, it is the two most distant points of an orbit and for earth, this value is 6378137 meters. Flattening is a measure of the compression of a circle or sphere along a diameter to form an ellipse or an ellipsoid of revolution (spheroid) respectively [26]. WGS 84 defines its reciprocal to be 298.257223563. According to World Book Encyclopedia, it takes 23 hours 56 minutes 4.09 seconds for the Earth to spin around once [27] which means in order to rotate 2π radians, it would take 86164.09 seconds. This result in an earth's moderate angular velocity to be 7292115.0×10^{-11}rad/s. The earth's gravitational constant is the result of the multiplication of the gravitational constant G and the mass M of the earth. The speed of light is the international standard for time. It is the maximum speed at which all matter and information in the universe can travel.

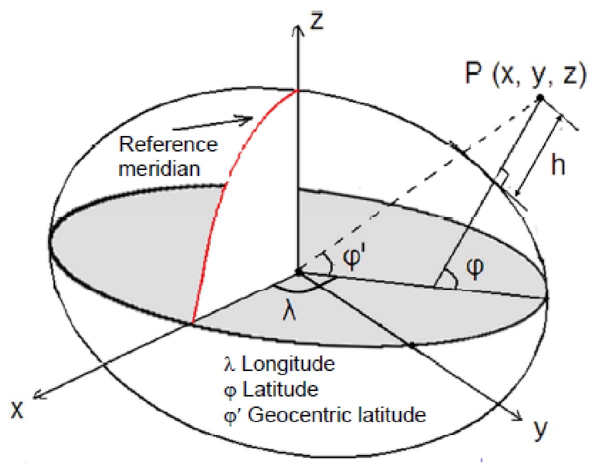

Figure 25. *Cartesian Coordinate and Geodetic Coordinate*

Table 10. *WGS 84 fundamental parameters*

Earth Model	*Semi-major axis a*	*6378137m*
	Reciprocal flattening 1/f	*298.257223563*
Earth's angular velocity	ω_E	*7292115.0*$\times 10^{-11}$*rad/s*
Earth's gravitational constant	*GM*	*3986004.418*$\times 10^{8} m^3/s^2$
Speed of light	*c*	*2.99782458*$\times 10^{8}$*m/s*

In order to get to the numerical relation between the Ellipsoidal coordinate and Cartesian coordinate, a clearer and more precise figure is shown as below. In this Figure 26, φ_l is the latitude, λ is the longitude and h denotes the height. Implementing the basic geometry to the figure, the following results, which are converting from Cartesian coordinate to Ellipsoidal coordinate can be obtained with $e^2 = 2f - f^2 = 0.0067$:

$$N = \frac{a}{\sqrt{1-e^2(\sin f)^2}} \text{ (1)}$$

$$x = (N+h)\cos\varphi_l \cos\lambda \text{ (2)}$$

$$y = (N+h)\cos\varphi_l \sin\lambda \text{ (3)}$$

$$z = (N(1-e^2)+h)\sin\varphi \text{(4)}$$

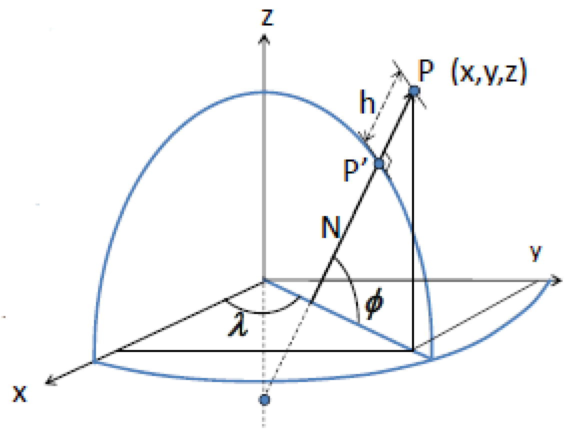

Figure 26. *Geometry between Ellipsoidal coordinate and Cartesian coordinate*

For example, with latitude φ=61.5 degree, longitude λ=23.5 degree and height of 300m, it is able to get the following results based on the formula above:

$$\varphi_l = 61.5 \text{ degree } \times \pi \div 180 = 1.0734$$
$$\lambda = 23.5 \text{ degree } \times \pi \div 180 = 0.41015$$
$$N = \frac{a}{\sqrt{1 - e^2(\sin f)^2}} = 6394689.3349$$
$$x = (N + h)\cos\varphi_l \cos\lambda = 2798340.2052$$
$$y = (N + h)\cos\varphi_l \sin\lambda = 1216752.9506$$
$$z = (N(1 - e^2) + h)\sin\varphi_l = 5582405.2377$$

On the contrast, the conversion from Cartesian coordinate to Ellipsoidal coordinate should also be taken into consideration since in general, the positioning is describe with latitude, longitude and height. The method discussed below is an iterative solution which means the whole procedure needs to be repeated several times in order to get the correct finalized result.

According to formula 2 and 3, it is obvious to get the following formula to calculate longitude λ:

$$\tan\lambda = \frac{y}{x} => \lambda = \tan^{-1}\frac{y}{x}$$

In addition, an intermediate parameter *p* is defined as:

$$p = \sqrt{x^2 + y^2} = (N + h)\cos\varphi_l$$

which gives the calculation of height h to be:

$$h = \frac{p}{\cos\lambda} - N$$

By combining the above formula with formula 4, the calculation of latitude φ can be obtained:

$$\tan \varphi_l = \frac{z}{p\left[1 - e^2\left(\frac{N}{N+h}\right)\right]}$$

For example, with Cartesian coordinate (2798340.2052, 1216752.9506, 5582405.2377), the corresponding latitude, longitude and height can be calculated using the above formulas:

$$\lambda = \tan^{-1}\frac{y}{x} = 0.4101524 => 0.4101524 \times 180 \div \pi = 23.5\ degree$$

$$p = \sqrt{x^2 + y^2} = 3051425.1829$$

First iteration, initialize φ=0:

$$N = \frac{a}{\sqrt{1 - e^2(\sin f)^2}} = 6378137$$

$$h = \frac{p}{\cos \varphi_l} - N = -3326711.8171$$

$$\varphi = \tan^{-1}\frac{z}{p\left[1 - e^2\left(\frac{N}{N+h}\right)\right]} = 1.0765 => 1.0765 \times 180 \div \pi = 61.6768 degree$$

After 5 times of iterations, the following result can be obtained:

φ_l=61.5 degree, h = 299.9949

6 Compass Simulator

The whole simulator is based on a software-defined GPS simulator designed for GPS which was provided by Finnish Geodetic Institute. According to the characteristics of Compass, modifications had been done to the original simulator to achieve the proper result for Compass satellites. The advantage of implementing a software-defined receiver is that it has more flexible design along with cost and power saving. The functions of processing unit, navigation unit as well as correlation, tracking and navigation tasks are all delivered by software.

Three major components which formed the simulation receiver are a RF front-end unit, a signal processing unit and a navigation processing unit. The signal received by the RF front-end is going to be amplified, filtered the noise, down-converted as well as going through automatic gain control and analogue-to-digital conversion which converts the received raw signal to a digital Intermediate Frequency(IF) data.

The main purpose of signal processing unit is to acquire the signal, track the code and carrier as well as demodulated the data. After data demodulation, the pseudorange measurements can be used by the navigation processing unit to obtain the Position, Velocity and Timing information.

6.1 Receiving Data

With the choosing of proper frequencies and bandwidth in Table 10, it is possible to get the raw data as in Figure 24:

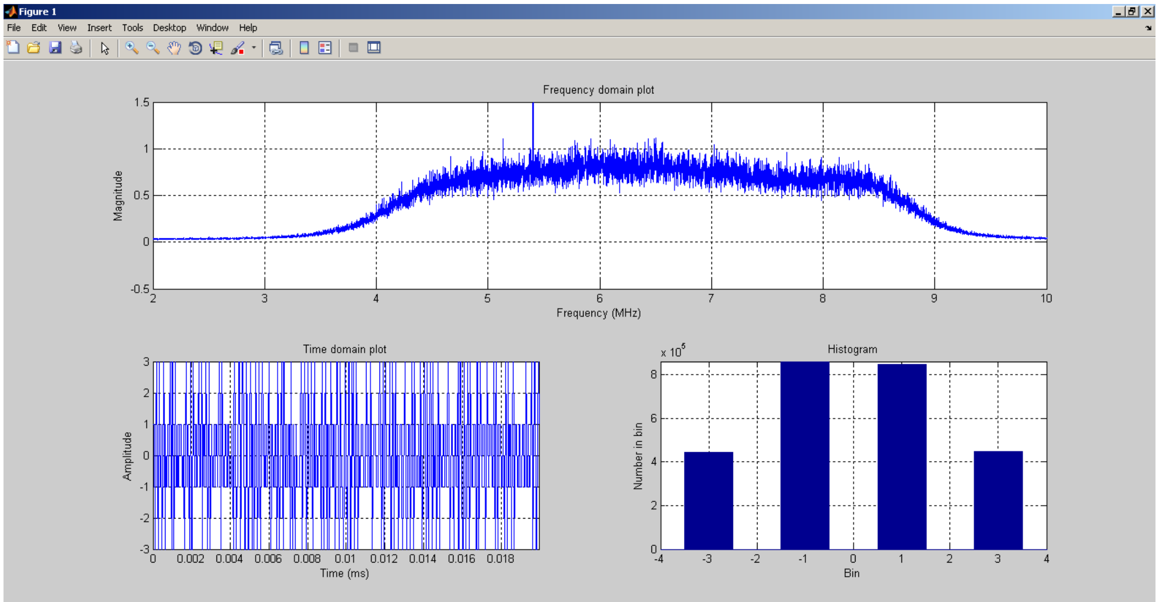

Figure 27. *Plot of received signal*

Table 11. *Front-End configuration for Compass signal reception*

Parameter	Value
Intermediate Frequency	6.5MHz
Sampling Frequency	26MHz
Number of Quantization bits	2bits

The frequency domain plot gives the spectrum of the signal that we received while in the bottom-left corner, the signal in the time domain is shown. In addition, the bin distribution is also given.

6.2 Acquisition Block

The main task of the signal acquisition block is to determine which satellites are visible to the client and then give a roughly estimate of the carrier Doppler and the code phase of those visible satellites.

During Acquisition, the PRN code of Compass is needed in order to do the DFT of the C/A code. The principle of the PRN code was shown in 3.2. Figure 25 below shows the plot of autocorrelation of PRN1 which the first sample is the most visible.

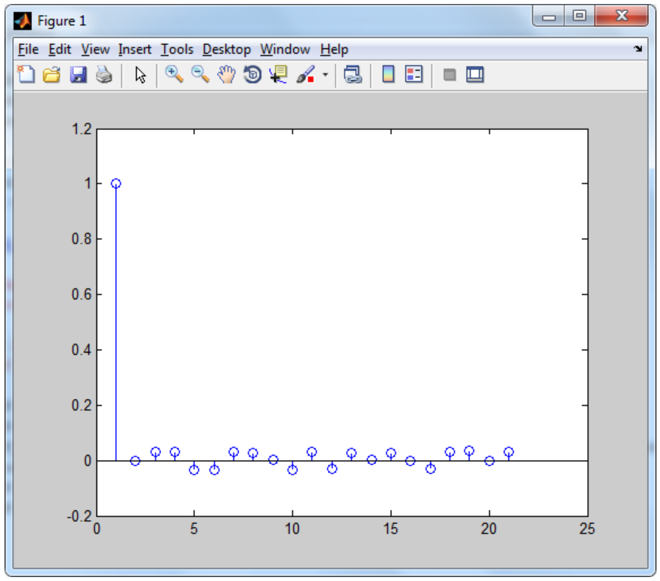

Figure 28. *Plot of Autocorrelation of PRN1*

A local carrier wave has been generated and then multiplied to the trunked signal after which an FFT correlation is carrier out. The result is then multiplied with the PRN in frequency domain which go through an IFFT correlation. In addition, the square of absolute value of the IFFT correlation is taken in order to find the peaks among all the correlation matrices.

For Compass IGSO and MEO satellites, the acquisition techniques used for GPS L1 C/A signal acquisition cannot be applied directly to acquire Compass B1-I and B2-I signal transmitted from IGSO and MEO satellites since there is additional NH code modulated on the original signal. With the NH code modulated on top of the navigation data bits, the data bit rate increased from 50 bps to 1 KHz. In addition, the sign changes of Compass B1-I and B2-I signal also occurs more frequently than that of GPS L1 C/A signal because of the presence of NH code modulated. Thus, if the sign information is not continuously preserved, then the acquisition method for Compass D1 signal with more than 1 millisecond coherent integration period may not work properly. Consider the sign transition issue, a special acquisition technique is implemented for Compass D1 signal which preserves the total useful energy in the presence of a sign transition so that a correct acquisition decision on the presence of the satellite can be made as well as its Doppler and the corresponding code phase. The working principle is as follows:

First, for a coherent integration period of T milliseconds, a X (T×1000) number of NH code bits is selected. For example, for a coherent integration of 5 milliseconds, the first 5 bits of NH code, i.e. [-1 -1 -1 -1 -1] is selected. In addition, a long incoming Compass signal of T+19 milliseconds is needed to carry out the FFT acquisition. In case of a coherent integration of 5 milliseconds, the long incoming signal will be 24 milliseconds.

Second, the frequency resolution needs to be defined. The frequency bin size should be less than two thirds of the coherent integration period which means in case of 5 milliseconds coherent integration period, the frequency bin size should be less than 133.33 Hz. After this, the selected X bits long NH code sequence is multiplied with the local generated Compass PRN codes in order to form an X bits long NH code modulated PRN code cycles.

The next step is to perform an FFT-based correlation between each T milliseconds blocks of incoming Compass signal and the local generated X bits long NH code modulated PRN code cycles.

Since the NH code length is 20 bits, there are in total 20 chunks of correlation matrices with all possible code delay and carrier Doppler combinations for a specific Compass satellite. The NH index used for detecting the presence of a satellite as well as the estimation of the carrier Doppler and the code phase is the one with the maximum correlation peak.

For Compass GEO satellites, there is no NH code modulated on top of the B1-I and B2-I signal. However, the date bit rate of B1-I and B2-I signal is 500bps which means each data bit will last for 2 milliseconds. Unlike the GPS L1 C/A signal that the bit transition occur only after 20 milliseconds, the bit transition for Compass D2 signal may occur every 2 milliseconds which means Compass D2 signal has a much frequent sign transition occurrences. Thus, a similar strategy for D1 signal acquisition can be implemented for Compass D2 signal.

First of all, because of the bit interval duration of D2 signal, the selected number of coherent integration summation should be even. For a coherent integration period of T milliseconds, a X = $\frac{T}{2} \times 1000$ number of data bits are selected. For instance, for a coherent integration period of 4 milliseconds, the number of data bits X will be 2. For X = 2, all possible combinations for incoming data bits will be $2^X = 4$. Thus, there will be four possible combinations for incoming received data bits which are [+1 +1], [+1 -1], [-1 -1], [-1, +1].

The choose of the frequency resolution is the same as for Compass IGSO and MEO satellites: the frequency bin size should be less than two thirds of the coherent integration time T. In case of a 4 milliseconds integration time, the frequency resolution should be less than 166.67Hz.

The next step is to multiply the 2^X data bit set with the local generated Compass PRN codes in order to get a T milliseconds long data modulated PRN code cycles. One thing needs to be taken into consideration is that while generating the date modulated PRN code cycles, the data bits should match with the local generated PRN code chip rate. After this, an FFT correlation is then calculated between the possible 2^X data bits combination of the incoming Compass signal and the local generated T milliseconds long data modulated PRN code cycles.

Since the length of the data bit set is 2^X, there will be in total 2^X chunks of correlation matrices with all possible code delay and carrier Doppler combinations for a specific Compass GEO satellite. The NH index used for detecting the presence of a satellite as well as the estimation of the carrier Doppler and the code phase is the one with the maximum correlation peak.

After implementing the above strategies (for Compass IGSO and MEO satellite, the NH code modulation is not implemented here), the acquisition result is as below, Compass PRN 05(GEO); 07, 09, 10(IGSO) and 11, 13, 14(MEO) were acquired.

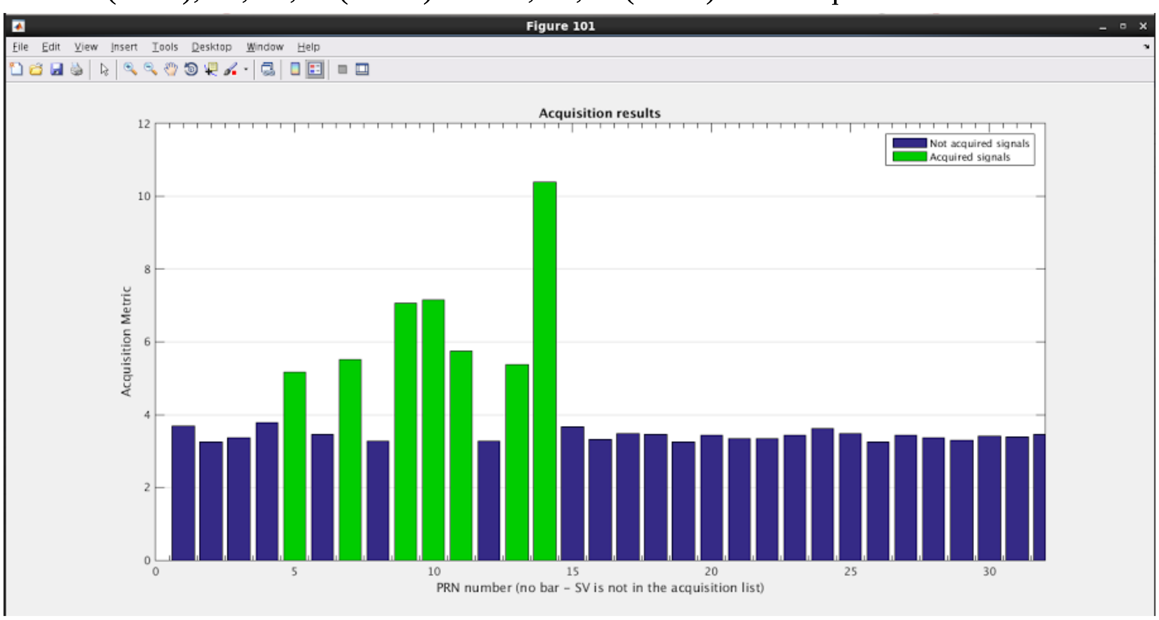

Figure 29. *Acquisition Result*

The major purpose when doing signal acquisition is to determine which satellites are visible to the users on earth as well as roughly estimate the carrier Doppler and the code phase of the satellites which are visible. The real-time field data was collected around 9.30AM UTC on 31st of January 2014 in Finnish Geospatial Research Institute, Finland.

7 Further Research and Conclusion

Due to lack of time, the tracking has not been implemented in this thesis. Therefore, the possible implementation of Compass tracking as well as the thesis conclusions are illustrated in this chapter.

As discussed in Chapter 3.3.2, since acquisition only provide a roughly estimation of the frequency and code phase parameters, it is the responsibility of the tracking block to refine those values, to keep tracking and to demodulate the navigation data from the specific visible satellite.

For Compass, there are two different kinds of navigation messages which are D1 telegraph with speed of 50 bps and D2 telegraph with speed of 500 bps. D2 telegraph message is broadcasted by GEO satellites. Since D2 telegraph obtains a relatively high transmission speed, the time of receiving signal is limited so that the sensitivity of signal tracking is relatively low. Thus, it is necessary to discover a tracking algorithm to enhance the sensitivity of signal tracking. [48]

In addition, due to the fact that all satellites are very high in the sky, the received signal is very weak. By using the tracking loop discussed in Chapter 3.3.3, the higher the bit error rate, the more chances are that the tracking loop will not work perfectly. Thus, to obtain a technique in order to successfully and accurately tracking weak signals is also important. [49]

Moreover, based on the services that Compass/Beidou-2 is currently able to provide, more and more experiments could be carried out in order to test the current service quality as well as engage Compass to a new field. For example, set up Compass system to vehicles in order to maintain their situations in real-time; smart watch that has Compass receiver installed for children and seniors and so on.

The whole thesis first briefly introduces GPS, Glonass and Galileo systems, and then more details of GNSS structure, principles and working flow are discussed. The characteristics and advantages of GNSS are illustrated.

With the public access to the documents published by Chinese government relative with Compass system, the Chinese Compass system officially went to the global service stage. Meanwhile, the Compass navigation industry keeps trying to develop Compass system in order to provide an excellent global service. For the long run, compared to other high accuracy positioning services, Chinese positioning system is still under developing and it will be a medium or long term which possibly result in tremendous grow in the next few years. The high accuracy positioning function ensures the accurate measurements of the position as well as increases the measurement efficiency. This can be widely implemented in small area measurement, construction measurement, precision navigation and other fields. The market of original surveying and mapping instrument is not as attractive as before; instead, the high accuracy GNSS products become more and more popular. The inward and outward of cruise and the landing of aircraft requires high accuracy; cruise and aircraft is able to maintain in the desired route by using high accuracy service; government can track and fight crimes through high accuracy positioning service. Currently, Compass navigation system is already used in some vehicle navigation devices, especially those built by Chinese manufacturers. However, the navigation speed is slow and somehow depends on GPS system. Based on the advantages of Compass, it will be implemented in the application of refining traffic such as accurate exit navigation in the highway, monitoring vehicles on the highway, auto-driving, bad traffic condition and other navigation situations.

Compass is differentiated with GPS by the code modulation method, satellite constellation, services provided and so on. When more than 4 satellites can be observed at the same time from the earth, more accurate navigation message can be achieved which ensures a much better positioning calculation. In addition, the use of software defined receiver is time and expenses saving. It does not require any kind of physical implementation and it is easy to be modified to process any kinds of signals in order to achieve the proper results.

Generally speaking, navigation and positioning services become more and more popular and are required in more and more field nowadays. The whole world is still investigating and researching to provide more accurate, fast, lower expenses and lower consumption navigation and positioning systems. These implementations will bring a lot of benefits not only to government usage but also for personal needs.

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