AN OPTIMIZED FFT BASED ACCQUISITION METHOD FOR GPS RECEIVERS

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by

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M.Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled "**AN OPTIMIZED FFT BASED ACCQUISITION METHOD FOR GPS RECEIVERS**" completed by **NEJAT YENİGÜN** under supervision of **ASSOC. PROF. DR. ENVER ÇAVUŞ** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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AN OPTIMIZED FFT BASED ACQUISITION METHOD FOR GPS RECEIVERS

ABSTRACT

Global Navigation Satellite Systems (GNSS) provides worldwide continuous accurate position, velocity and time information to civilian and military users. This kind of access enabled usage of GNSS at various applications ranges from agriculture to finance. The most commonly known and used navigation satellite system is Global Positioning System (GPS) provided by USA. Glonass (Russia), Galileo (European Union), BeiDou (China) are the other types of GNSS. Each GNSS has different signals designed for different purposes. Therefore, flexible solutions should be implemented to handle these diverse signals. GNSS Software Defined Radio (SDR) answers this problem in terms of flexibility, modularity and upgradability.

GNSS receiver, which is used in this work, is a multi-constellation, multi frequency SDR developed by TÜBİTAK SAGE. This thesis presents the implementation of the aforementioned SDR limited to GPS L1 signal. The SDR was built using FPGA and microprocessor for real time implementation.

Acquisition and tracking are the main tasks which consume the most processing power for SDR solutions. Besides SDR, a novel optimized FFT based acquisition method is proposed in order to reduce acquisition process load.

Keywords: GPS receivers, signal acquisition, down sampling, resource consumption, fast Fourier transform

GPS ALICILARI İÇİN OPTİMİZE EDİLMİŞ FFT TABANLI SİNYAL YAKALAMA YÖNTEMİ

ÖZ

Uydu tabanlı küresel konumlama sistemleri(KKS) sivil ve askeri kullanıcıları için dünya genelinde sürekli doğru pozisyon, hız ve zaman bilgisi sağlarlar. Bu tarzdaki erişimi, tarımdan finansa bir çok uygulama için uydu tabanlı küresel konumlama sistemlerini kullanılabilir hale getirmiştir. En çok bilinen ve kulanılan küresel konumlama sistemi ABD tarafından sağlanan GPS'tir. Glonass(Rusya), Galileo(Avrupa Birliği), BeiDou(Çin) diğer uydu tabanlı küresel konumlama sistemleridir. Her bir küresel konumlama sistemi değişik amaçlar için tasarlanmış farklı sinyallere sahiptir. Bu nedenle farklı farklı sinyalleri işleyebilmek için esnek çözümler geliştirilmelidir. Küresel konumlama sistemleri için yazılım tabanlı radyolar bu problemi esneklik, modülerlik ve yükseltilebilirlik açısından çözerler.

Bu çalışmada kullanılan küresel konumlama sistemi alıcısı, birden fazla sistemi ve birden fazla sinyal frekansını destekleyen ve TÜBİTAK SAGE tarafından geliştirilen yazılım tabanlı bir alıcıdır. Bu tez bahsi geçen alıcının yalnızca GPS L1 frekansı için uygulamasını hedef alır. Yazılım tabanlı alıcı FPGA ve işlemci kullanılarak gerçek zamanlı işlemler için tasarlanmıştır.

Uydu yakalama ve takip etme yazılım tabanlı alıcılar için en çok işlem gücü tüketen görevlerdir. Yazılım tabanlı alcının yanında hızlı Fourier dönüşümü tabanlı uydu yakalama yöntemleri için işlem gücünü optimize eden yeni bir metod önerilmiştir.

Anahtar Kelimeler: KKS alıcıları, sinyal yakalama, seyreltme, kaynak tüketimi, hızlı Fourier dönüşüm

CONTENTS

NOMENCLATURE

Acronyms

GPS	Global Positioning System
PRN	Pseudo Random Noise
C/A	Coarse Acquisition
L1	Link 1
FFT	Fast Fourier Transform
BPS	Bits Per Second
PVT	Position Velocity Time
ASIC	Application Specific Integrated Circuit
SDR	Software Defined Radio

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CHAPTER 1

INTRODUCTION

Global Navigation Satellite Systems (GNSS) usage has been rapidly increasing in accordance with new application areas. The number of GNSS receivers was nearly 6 billion in 2017, [1] . GNSS users could obtain position, velocity and time anywhere on earth, free of charge.

GNSS stands for generic term of the satellites that transmits signals which are designed for navigation purposes. Today, there are four independent GNSSs in fully/partially service. The first navigation satellite system is Global Positioning System (GPS) which was developed by USA and fully operational since 1995 [2]. Russia Federation has developed GLONASS system which was also fully operational by late 2011, [2]. GPS and GLONASS are the widely used systems in multi-constellation GNSS receivers. European Galileo and Chinese BeiDou system are currently in the deployment phase and are expected to be operational by 2020. The increased number of satellites comes with many opportunities. Availability of navigation signals for urban areas, redundancy and enhanced accuracy are the most up and coming benefits.

GPS receivers are critical part of a modern navigation system. In modern navigation systems, inertial navigation systems are used for main sub systems. Although inertial navigation systems can provide position and attitude information at high rates, the magnitude of the error on position and attitude information grows with the propagating time. Therefore, an assistance navigation system should be used with inertial navigation systems. Because of the low cost, high precision and accuracy, GPS receivers are the mostly used assistance system nowadays [2].

In GPS receivers, the position information is dependent on the tracking of the signals which comes from GPS satellites at the earth’s orbit. GPS receivers provide position, velocity and time information by calculating the information which consist of GPS satellites' position and pseudo range. This information is obtained by tracking the GPS satellites' signals.

From the onset, the GPS receivers are designed to use analog components as in the 1970's. The digital GPS receivers were produced in 1980's. ASIC and microprocessor based GPS receivers are used with the technological improvements at the following years [3]. These types of GPS receivers provide navigation solutions at low cost and low power. On the other hand, ASIC based GPS receivers cannot provide flexibility and configurability in terms of signal processing because of the structure of ASIC technology. Nowadays, software defined radios are popular since their flexibility and configurability are attainable. At software defined GPS receivers, the analog GPS satellites' signals which comes from GPS receivers' antenna are converted to digital signals at front end chips. Then, with the help of microprocessors and FPGA, the digital signals are processed while position, time and velocity information are obtained. Software defined GPS receivers are not suitable for real time applications because they make use of only microprocessors and these microprocessors don't have enough processing speeds for GPS receiver applications. For real time applications, some of the receiver processes should be implemented on FPGA. Therefore, resource consumption in FPGA have critical importance at GPS receiver implementation. Furthermore, with the new signals added GPS space segment, the resource consumption of FPGA increases due to the necessity for processing new signals.

In literature, there are plenty of acquisition methods are defined. [4], [5], [6], [7] and [8] describe the FFT based acquisition methods in details. For an increased processing speed, parallel acquisition methods are preferred. Since FFT based methods have parallel processing capability, they are adopted in acquisition blocks and various optimization techniques is applied in FFT blocks. For example, sparse FFT method is described in [9]. Reduced size FFT method is proposed in [10]. In [11], resampling strategy and variable circular correlation method are presented. Averaging correlation method is described in [12]. These proposed methods are strategies for optimization in FFT size.

In this work, a method which optimizes the resource consumption and computational complexity in acquisition phase of GPS signals is proposed for FPGA based GPS receivers. Basically, a down sampling block is used for decreasing FFT size. A band pass filter is designed and used for preventing the aliasing effect which is the side effect of down sampling process.

The remainder of this thesis is organized as follows: GPS overview is mentioned in Chapter 2. In Chapter 3, acquisition and tracking processes are discussed. In Chapter 4, the proposed acquisition method is described and the implementation results about this method are given. Additionally, while developing the method, the problems occurred are identified. In the last chapter, the conclusion is given.

CHAPTER 2

GLOBAL POSITIONING SYSTEM OVERVIEW

In this Chapter, a review of Global Positioning System (GPS) is given. For an in depth treatment of a GPS system, the readers are referred to [4], [5], [6], [7] and [8]. The Global Positioning System which provides position, velocity and time information to its users consists of three segments: user, control and space. The space segment consists of GPS satellites. This segment produces the signals needed to compute position and time information and also it is responsible for the transmission of the signals. The control segment has the task of troubleshooting the errors in the space segment and informing the user segment about these errors, such as the clock or ephemeris errors. User segment computes its own position, velocity and current time by processing signals from the GPS satellites. GPS works according to the logic of the simple receiver and complex transmitter.

Finding position, velocity and time information is described in detail at [7]. Computing position information is dependent on trilateration principle. Trilateration principle explains that the user position can be calculated by using the range between user and known locations. The 2 dimensional version of trilateration is illustrated in Figure 2.1. In Figure 2.1 there are three stations and one point which position information is needed. These three stations' coordinates are known by the user and also the ranges between the point and the stations are also known. Then, the point position can easily be calculated. For GPS receivers, at least 4 satellites' navigation information is needed to calculate receiver position since position information has three unknowns such as latitude, longitude and height and also the time information is needed. There are 4 unknowns, therefore, 4 known parameters are needed to calculate unknowns.

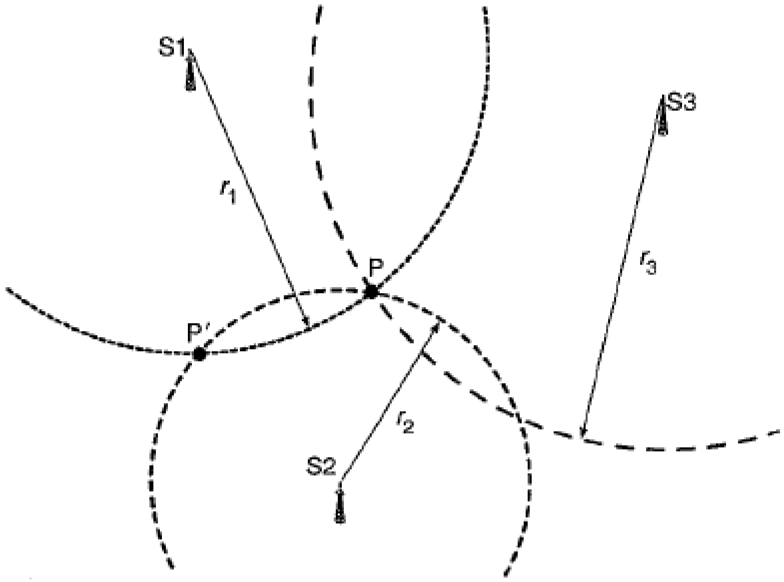


Figure 2.1 Trilateration [7]

2.1 GPS L1 C/A Code Signal Structure

GPS L1 C/A Code Signal Structure is described in detail in [13]. The transmitting frequency of carrier signal is 1575.42 MHz. The GPS L1 C/A signal consists of three main parts. The first part is the carrier signal, the second part is the data part and the third part is the code part. In Figure 2.2, the structure of GPS L1 C/A code is illustrated.

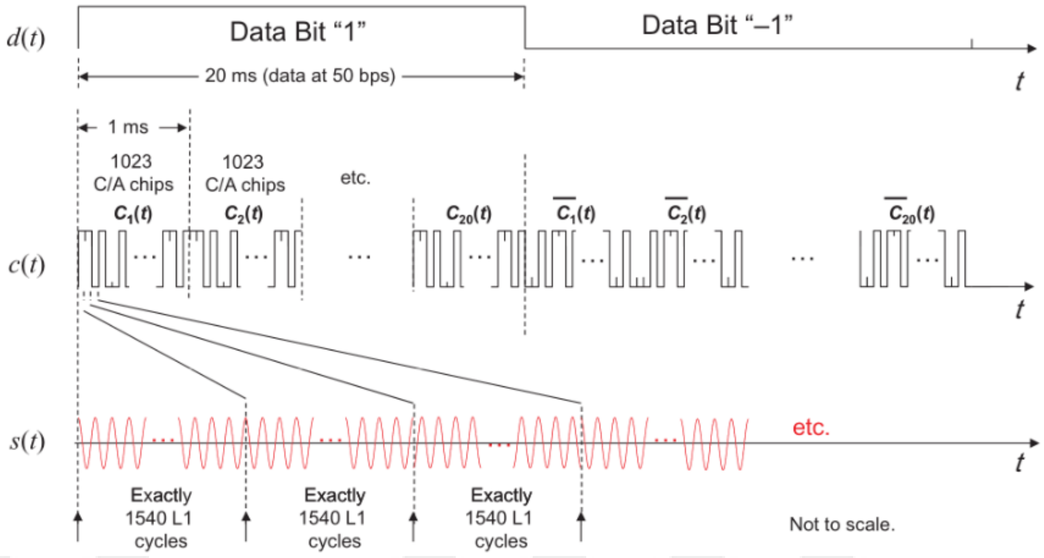


Figure 2.2 GPS C/A signal structure at L1 [13]

The frequency of carrier signal is 1575.42 MHz. The data bits of the signal are modulated by the binary phase shift keying structure. Although all satellites are transmitting on the same frequency, the signals sent by all satellites can be distinguished at the same time, since GPS is a code division multiple access (CDMA) system.

The data portion contains ephemeris information, almanac and other navigation parameters. Ephemeris parameters are the parameters which are required to compute the satellite positions and current time. The rate at which data is sent is 50 bps. Thus, every data bit is sent in 20 milliseconds. The GPS receiver is responsible for collecting these bits and converting them into a meaningful navigation message.

The code part is called coarse acquisition (C/A) code or pseudo random noise (PRN). Each bit of this code is called a chip. It consists of a total of 1023 chips and repeats itself every 1ms. Thus, the chipping rate of the C/A code is 1023 MHz. The correlation properties of these codes are very important for the design of the GPS receiver. There are two basic features. The first one is nearly no cross correlation. The other is high autocorrelation. Thanks to these features because codes from different satellites can be distinguished from each other. To be more precise in tracking the incoming signals from satellites, the signals should be identified. By using auto and cross correlation property of the C/A codes, GPS satellite's signal can be detected by GPS receiver.

As shown in Figure 2.3, at the right, the autocorrelation property of PRN1 is high, on the other hand the cross correlation property of PRN1 and PRN2 is low.

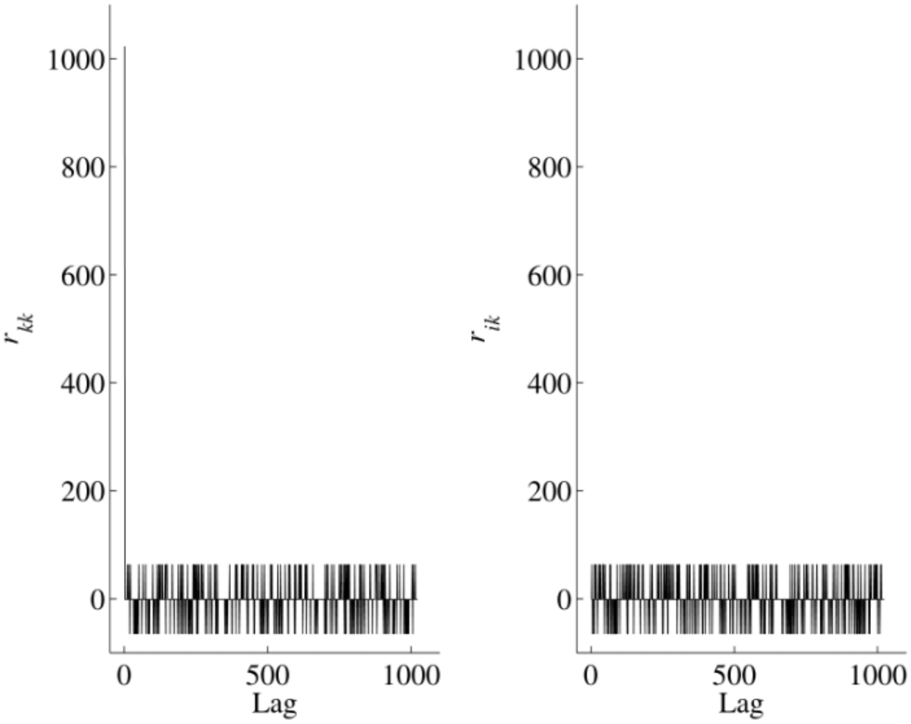


Figure 2.3 Auto and cross correlation property of L1 C/A signals [5]

2.2 The Math behind Acquisition and Tracking

This part is described in detail in [5] and [6]. GPS L1 signals are transmitted at 1575.42 MHZ RF frequency. Then, when this radio frequency signal reaches the GPS receiver, this signal is reduced to an intermediate frequency to be processed. This process is called down conversion and is obtained by multiplying the incoming GPS signal and the signal generated by the local oscillator of the GPS receiver at certain frequency. The signal at intermediate frequency is also sampled by the analog to digital converters of the GPS receiver at specific operating frequencies. After the signal is returned to the digital signal, it is processed by the receiver and the necessary outputs are calculated. The block diagram of these operations is given in the Figure 2.4.

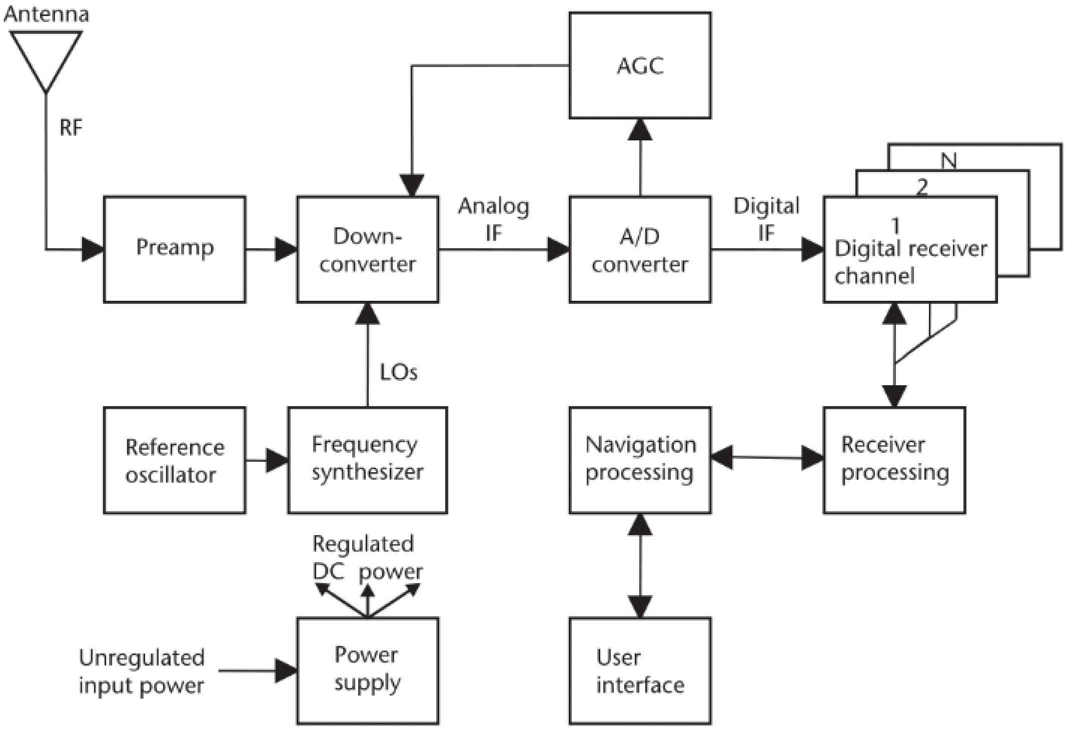


Figure 2.4 Generic digital GPS receiver block diagram [6]

The resultant down converted signal is mathematically expressed as follows:

$$s_k(t) = 2P_c\, C_k(t)D_k(t)cos(w_{if}t) + 2Pp_{l1}P_k(t)D_k(t)sin(w_{if}t) \qquad \mathbf{(2.1)}$$

where $s_k(t)$ is the signal of satellite k, P_c and $2Pp_{l1}$ is the power of the C/A and P code respectively, $C_k(t)$is the C/A code sequence, $D_k(t)$ is the navigation data, $cos(w_{if}t)$ and $sin(w_{if}t)$ is the carrier signals of C/A code and P code respectively and $P_k(t)$ is the precision code sequence. Since the precision code is not under consideration of this work, the resultant signal is simply as

$$s_k(t) = 2P_c\, C_k(t)D_k(t)cos(w_{if}t). \qquad \mathbf{(2.2)}$$

The signal is sampled at sampling frequency fs. The digitized signal is

$$s_k(n) \ = C_k(n)D_k(n)cos\left(w_{if}n\right) \ + e(n) \qquad \mathbf{(2.3)}$$

where n is the unit and it is 1/fs, $e(n)$ is the noise term because of digital sampling. The major aim of acquisition and tracking is to acquire the navigation data and to track the coarse acquisition code from the received signal, precisely.

In both acquisition and tracking processes, the concept called carrier wipe off draws much attention. This process is simply that the locally generated carrier signal is tried to be exactly the corresponding incoming signal and then these two signals multiply with each other. Mathematically, it can be explained why this process is called carrier wipe off. The incoming signal and locally produced signal is simply as

$$s_k(n) \ = \ C_k(n)D_k(n)cos\left(w_{if}n\right) \qquad \mathbf{(2.4)}$$

Then if the multiplication between them is performed, the resultant signal is

$$s_k(n) = \ C_k(n)D_k(n)cos\left(w_{if}n\right)cos\left(w_{if}n\right)$$

$$= 0.5 \ C_k(n)D_k(n) + \ 0.5cos\left(2w_{if}n\right)C_k(n)D_k(n) \qquad \mathbf{(2.5)}$$

The double intermediate frequency term can be cancelled by applying low pass filter. This equation gives us carrier free $0.5 \ \mathrm{C_k(n)D_k(n)}$ term only. Thus, this process is called carrier wipe off and also the resultant signal is at baseband.

CHAPTER 3

GPS L1 C/A ACQUISITION AND TRACKING PROCESS

The acquisition and tracking process for GPS L1 civilian signals is described in detail in [4],[5] ,[6],[7], [8] and [13]. To provide PVT solution in a GPS receiver, the code phase and the Doppler frequency of the carrier must be determined. The receiver must track these parameters to keep providing PVT solutions. There are two different processes for determining the code phase and the Doppler shift of the carrier. These processes are acquisition and tracking. The purpose of acquisition is to determine the frequency of the carrier and the code phase coarsely. To be more precise, there are two outputs of the acquisition process. The first one is the Doppler frequency of the specified satellite's signal. The second one is the code phase. These two outputs will be given in detail in the following sections.

3.1 Doppler Effect

Doppler Effect is described in detail in [8]. Even though the frequencies of the carrier signals for each satellite are the same, they reach the receiver in different frequencies due to the Doppler Effect.

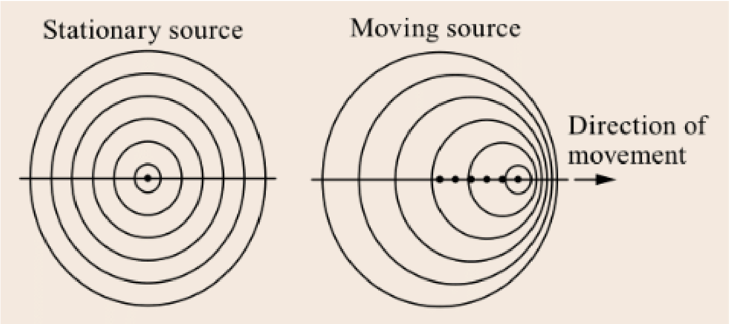


Figure 3.1 Doppler effect [8]

The Doppler Effect is that, as can be seen from Figure 3.1, if a wave source moves and an observer measures the frequency of the wave, the frequency of the wave increases if the wave source moves toward the observer and the frequency of the wave going in the opposite direction decreases. This means that because the GPS satellites have a certain speed relative to the GPS receiver, their signals’ frequency changes due to the Doppler Effect. If satellites are converging with the receiver, the frequency of the signal is increased otherwise it is decreased.

3.2 Code Phase

Code phase phenomenon is described in detail in [6]. From the moment the satellite signal is generated, it takes a certain amount of time to arrive at the receiver. In order to capture this signal, the receiver generates the same signal called replica code. After the replica signal is generated, this signal is correlated with the incoming signal.

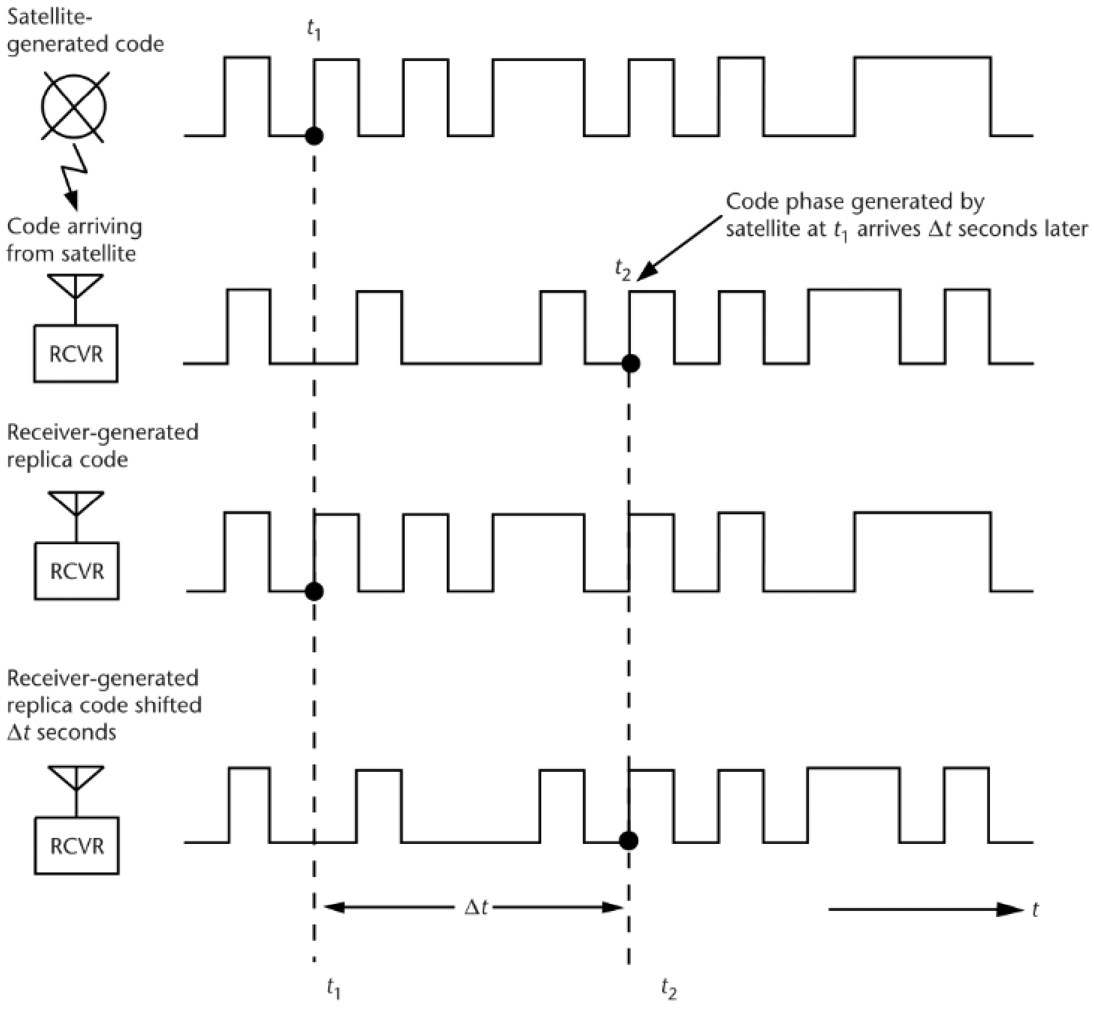


Figure 3.2 Code phase [6]

As can be seen from Figure 3.2, the signal is generated at time t1. This signal reached the receiver at time t2. The receiver must shift the replica code that it generates in order to lock it. This time difference is called code phase and is expressed as a chip. In other words, the code produced by the receiver deviates from the actual code expressed by the code phase.

3.3 Acquisition Methods

Acquisition methods are described in detail in [5]. Specific methods have been developed to find the above mentioned Doppler frequency and code phase. At the following sections these methods will be described.

In general, there are three basic methods for acquisition. These methods are serial search acquisition, parallel frequency space search acquisition and parallel code phase search acquisition. These three basic methods will be explained at following sections.

3.3.1 Serial Search Acquisition

As mentioned before, the entire purpose of the Acquisition process is to find out Doppler frequency and code phase coarsely. For this purpose, it can be said that there is a two-dimensional search space that we need to search. The one dimension of this space is code phase and the other is the Doppler frequency. Briefly, the aim of acquisition is to determining the point where the Doppler frequency and code phase of the signal corresponds to.

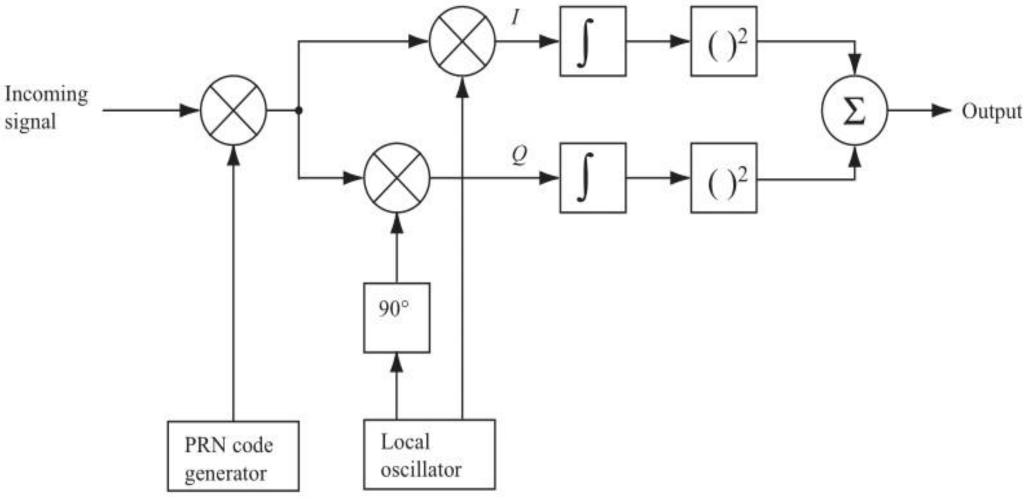


Figure 3.3 Serial search acquisition [5]

As shown in Figure 3.3, first of all, the incoming signal is multiplied by the replica code generated by the receiver. This product is multiplied by both the cosine and the sine portion of the carrier signal produced locally, since the carrier phase of the incoming signal is not known. The result that consists of multiplication by the cosine of local oscillator is called the in-phase component and the result of the multiplication by the sine of local oscillator is called as quadrature component.

The in phase and quadrature components of the signal are firstly integrated, then squared and added. These value is compared with a predetermined threshold in order to determine whether the desired signal is available or not. This method is power and time consuming. In order to use this method, all of the satellites in GPS constellation must be considered and for each satellite, locally produced code must be generated. For each code there are 1023 chips in total, thus, 1023 different versions of this code must be generated and multiplied. Finally, the Doppler frequency is required to be searched in a search space of 20 KHz in total at 500 Hz intervals plus 10 KHz and minus 10 KHz [5].

This leads us to the conclusion that the processes described in the Figure 3.3 must be done 1023 * (2 * (10000/500) + 1) times. Therefore, a total of 41943 different combinations of this calculation are required [5].

3.3.2 Parallel Frequency Space Search Acquisition

As mentioned before, the serial search acquisition is a time consuming method. The parallel frequency space search algorithm allows you to search the required frequency space for acquisition in parallel.

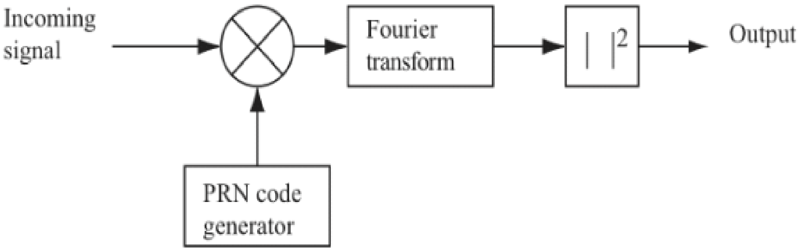


Figure 3.4 Parallel frequency space search acquisition [5]

As shown in Figure 3.4, the GPS receiver must generate local PRN code for this algorithm. The locally generated PRN code is multiplied by the incoming signal like serial search acquisition algorithm.

After the codeless signal is acquired, the presence and the frequency of the desired signal can be determined by means of Fourier transform. When the local PRN code is perfectly aligned with the incoming signal, the resulting signal is purely sinusoidal if the desired satellite is available. If any peak is present at the Fourier transform of this signal, the Doppler frequency of the incoming signal can be determined. In order to implement this method, a 1023 different version of locally generated code is required because the code phase is not known. In addition, the Fourier transform should be implemented. Therefore, it is faster than serial search acquisition method, however, the complexity of the parallel frequency space search acquisition is higher than the serial search acquisition.

3.3.3 Parallel Code Phase Search Acquisition

The search for the code phase can also be parallelized. This is a very valuable feature because it has eliminated the need to search sequentially the 1023 different code phases. Because of this reason, it is faster than parallel frequency search space method.

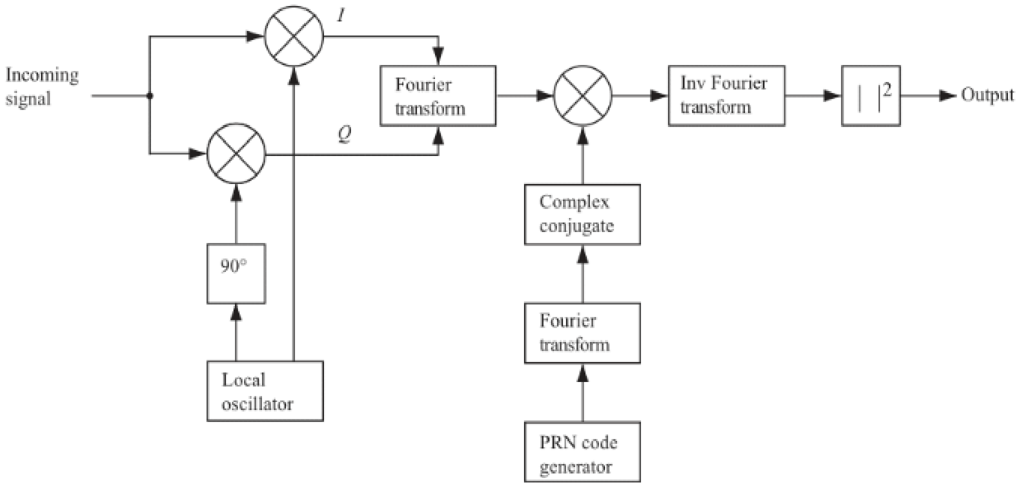


Figure 3.5 Parallel code phase search acquisition [5]

As shown in Figure 3.5, firstly, the incoming signal is multiplied by both the sine and cosine portion of the locally produced carrier. The result of this multiplication is in the in phase and quadrature part of the signal. Therefore, this resultant signal is a complex signal. After that, the Fourier transform of the complex signal and the complex conjugate Fourier transform of the replica code is multiplied. This operation corresponds to multiplication in the frequency domain; thus, this implies that it is the circular correlation in the time domain. To transform the result into the time domain, the inverse Fourier transform is applied in the resultant signal. If any peak is observed at the result, then, the index of this peak gives us the code phase of the incoming signal. The frequency of the locally produced carrier signal at the peak gives us the frequency of the incoming signal. In this method, the GPS receiver must generate 41 different versions of the carrier signal since 20 KHz search space is required for acquisition with

500 Hz steps. Although this is the most rapid one between the mentioned algorithms, it is the most expensive method since it uses three Fourier transform block.

3.4 Acquisition and Tracking Blocks

At this section, the local signal and the replica code generator will be explained. How they are produced and used in GPS receiver will be described.

3.4.1 Local Carrier Generator

This subject is described in detail in [6]. Numerically controlled oscillators are used in many applications as frequency synthesizers. Since both locally produced carrier and code signals have frequency portion, the numerically controlled oscillators have critical importance at GPS receivers.

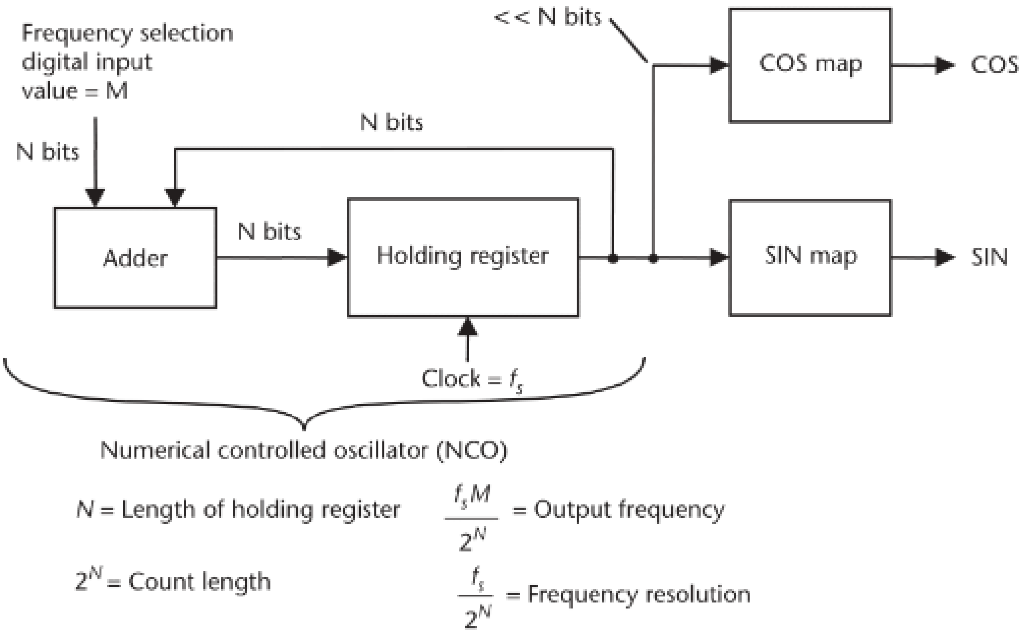


Figure 3.6 Numerically controlled oscillator [6]

As can be seen from Figure 3.6, basically, a numerically controlled oscillator consists of three main components that are adder, holding register and mapping function. At every clock pulse at frequency f_s , the N bits holding register value is summed up with the frequency selection input M. The result is again saved in the holding register. The crucial point is that after some time the N bits holding register will be overflowed. By using the most significant K bits of the holding register, the mapping function can be driven. To be more precise, let us say that the clock frequency f_s is 200 MHz, the holding register is 10 bits and we want to produce 25 MHz cosine signal which will be used as replica carrier signal. The output frequency is f_s* M /$2^N$and then M = 25 / (200 * 2^{10}) = 128. M must be chosen as 128 to produce 25MHz cosine signal and let us say that the 8 quantization level cosine signal is desired. The most significant 3 bits of the holding register will be used to produce cosine signal.

Table 3.1 Numerically controlled oscillator phases [6]

3 bits value	cosine output value
000	1
001	0.7
010	0
011	-0.7
100	-1
101	-0.7
110	0
111	0.7

The cosine in Table 3.1 can be used as mapping function in the numerically controlled oscillator and the 3 bit holding register at output frequency drives the table. Actually, there are also negligible errors that occur at this design. The frequency resolution which gives the minimum detectable or producible frequency is f_s / 2^N. Hence, if it is not at negligible level this is the problem for GPS receiver. The numerically controlled oscillator is so important for GPS receiver since both replica carrier and replica code frequency is produced by this block.

3.4.2 Local Code Generator

There are two methods for generating local prn code. The first one is using a two dimensional table which is preloaded before receiver operations. This table contains one GPS L1 C/A code for each satellite and totally 1023 chips for 32 satellites. Since this table consumes pre allocated memory, this method is used by software based receivers. The second method is creating a logic unit which produces the L1 C/A codes at every clock pulse, like a GPS satellite code generator. This method is preferred by FPGA based GPS receivers since it consumes only logical slices. The method is described in Figure 3.7. The local code generator block contains two shift registers, the first one is G1 and the second one is G2 register. Both of the registers are 10 bits wide. At every clock pulses, these two registers shift their values and also at the same time the feedback values are fed to these registers. The feedback values are calculated for G1 register by doing XOR operation with the third and tenth bit values. For G2 register, the feedback value is calculated by doing XOR operation with second, third, sixth, eighth, ninth and tenth bit values. Lastly, the output values of the registers are XORed with each other. The resultant value is the C/A code sample at the clock pulse. The initial values of the registers are all one.

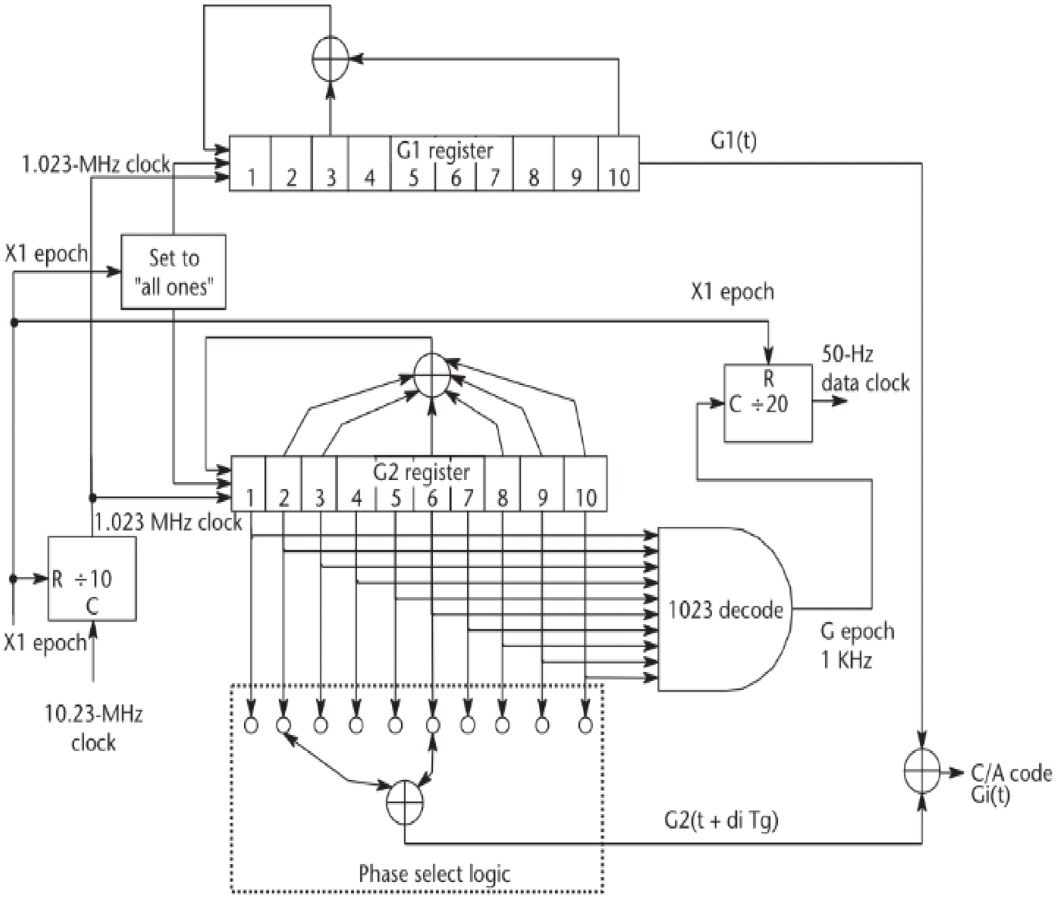
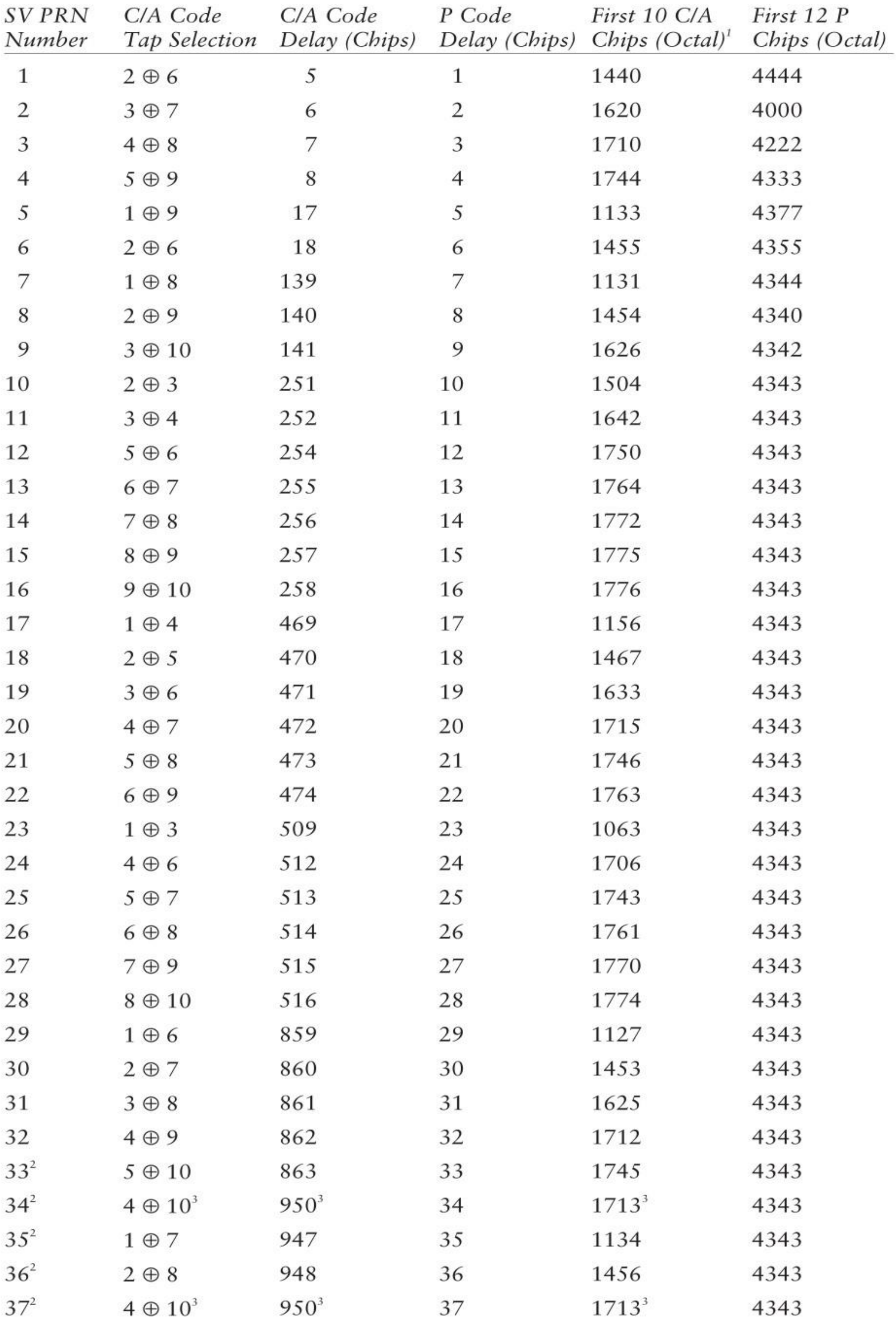


Figure 3.7 GPS L1 C/A code generator [6]



SV PRN Number	C/A Code Tap Selection	C/A Code Delay (Chips)	P Code Delay (Chips)	First 10 C/A Chips (Octal)[1]	First 12 P Chips (Octal)
1	2 ⊕ 6	5	1	1440	4444
2	3 ⊕ 7	6	2	1620	4000
3	4 ⊕ 8	7	3	1710	4222
4	5 ⊕ 9	8	4	1744	4333
5	1 ⊕ 9	17	5	1133	4377
6	2 ⊕ 6	18	6	1455	4355
7	1 ⊕ 8	139	7	1131	4344
8	2 ⊕ 9	140	8	1454	4340
9	3 ⊕ 10	141	9	1626	4342
10	2 ⊕ 3	251	10	1504	4343
11	3 ⊕ 4	252	11	1642	4343
12	5 ⊕ 6	254	12	1750	4343
13	6 ⊕ 7	255	13	1764	4343
14	7 ⊕ 8	256	14	1772	4343
15	8 ⊕ 9	257	15	1775	4343
16	9 ⊕ 10	258	16	1776	4343
17	1 ⊕ 4	469	17	1156	4343
18	2 ⊕ 5	470	18	1467	4343
19	3 ⊕ 6	471	19	1633	4343
20	4 ⊕ 7	472	20	1715	4343
21	5 ⊕ 8	473	21	1746	4343
22	6 ⊕ 9	474	22	1763	4343
23	1 ⊕ 3	509	23	1063	4343
24	4 ⊕ 6	512	24	1706	4343
25	5 ⊕ 7	513	25	1743	4343
26	6 ⊕ 8	514	26	1761	4343
27	7 ⊕ 9	515	27	1770	4343
28	8 ⊕ 10	516	28	1774	4343
29	1 ⊕ 6	859	29	1127	4343
30	2 ⊕ 7	860	30	1453	4343
31	3 ⊕ 8	861	31	1625	4343
32	4 ⊕ 9	862	32	1712	4343
33[2]	5 ⊕ 10	863	33	1745	4343
34[2]	4 ⊕ 10[3]	950[3]	34	1713[3]	4343
35[2]	1 ⊕ 7	947	35	1134	4343
36[2]	2 ⊕ 8	948	36	1456	4343
37[2]	4 ⊕ 10[3]	950[3]	37	1713[3]	4343

Figure 3.8 GPS L1 C/A code tap selection [6]

The output value of G1 register is fixed at tenth bit value before clock pulse. However, the output value of G2 register is variable for producing totally 37 different C/A code. At Figure 3.8, the G2 register output values are shown for specific satellites. By using these tap combinations, different C/A codes are produced. For example, for satellite one the G2 register output values are second and sixth bits. These two values XORed, then G2 register output value is generated.

3.5 Tracking

Tracking process is the heart of the GPS receiver. The most crucial point is that the produced replica signal should align with the received signal as accurate as possible. If this alignment accuracy is at desired level, then, the computed position of the GPS receiver is at the desired level also. However, the replica signal cannot track the received signal appropriately, then, the computed position will not be accurate. Since the aim of the tracking process is to align the replica signal with the received signal, the quality of the GPS receiver is mostly dependent of the tracking process. After acquisition process, there are two outputs, they are the code phase and carrier frequency of the received signal. These two outputs are the inputs of the tracking channel of the GPS receiver. At the tracking process, the coarse values of code phase and carrier frequency are precisely tracked at fine values. There are two types of tracking loops. The first one is the carrier tracking process and the second one is the code tracking process. While these loops are under operation, the discriminator and the filter blocks work with them also.

3.5.1 Carrier Tracking

This subject is described in detail in [6] and [8]. The duty of the carrier tracking block at the GPS receiver is tracking the carrier frequency of the incoming signal precisely.

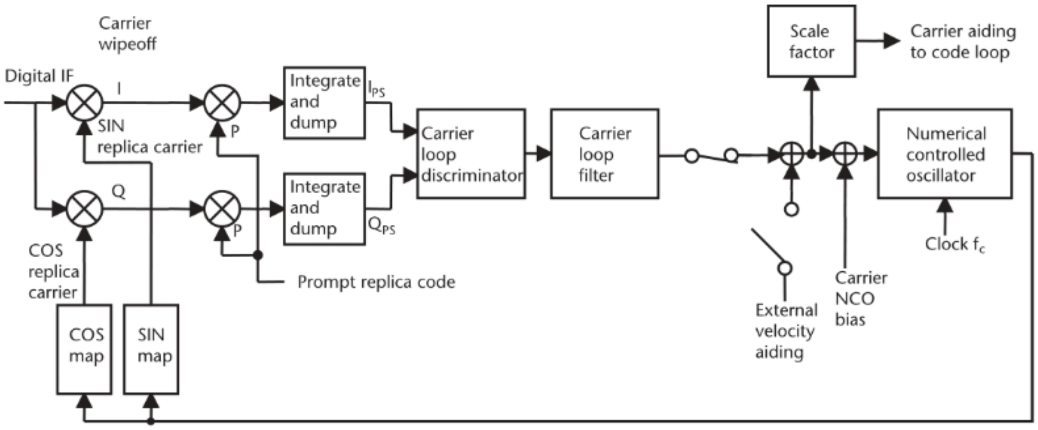


Figure 3.9 Carrier tracking loop [6]

By looking at Figure 3.9, the carrier tracking can easily be understood. The first operation of this block is carrier wipe-off. By using the numerically controlled oscillator of the GPS receiver carrier tracking block, the frequency of the replica signal is adjusted. Initially, this replica signal frequency is set to the intermediate frequency plus the specific Doppler frequency of the tracked satellite which is calculated at acquisition phase. After the determination of the carrier frequency by using the cos and sine map, the in phase and quadrature components of the carrier signals are produced. The other input of the carrier tracking block is the prompt replica code; this prompt replica code will be described in the next section. At every clock pulse, the carrier wipe-off process is done, then, the produced in phase and quadrature component of the carrier signal are multiplied with the prompt replica code. The result is accumulated at the specific register. When the dump signal is triggered, the in phase and quadrature component of the result is saved and they will be the input of the carrier loop discriminator. The dump signal is generated at the end of the C/A code signals, however, it doesn’t have to be one C/A code sequence, it may be multiple of them. The time between two dump signals is called integration time. The carrier loop discriminator simply calculates the error which is the difference between incoming signal phase and replica carrier phase. After the error term is calculated at the discriminator, the error term will be filtered by the carrier loop filter, since the discriminator output is very noisy. The carrier loop filter is simply a controller. This controller uses the numerically controlled oscillator to fix the carrier frequency at desired value.

3.5.2 Code Tracking

This subject is described in detail in [6] and [5]. The duty of the code tracking block at the GPS receiver is tracking the code phase of the incoming signal precisely. To understand the code tracking loop, the correlator term should be described. The correlators are one chip delayed, aligned and one chip early version of the replica code signal. The delayed correlator name is late correlator. The name of the aligned one is prompt correlator. The name of the early one is early correlator.

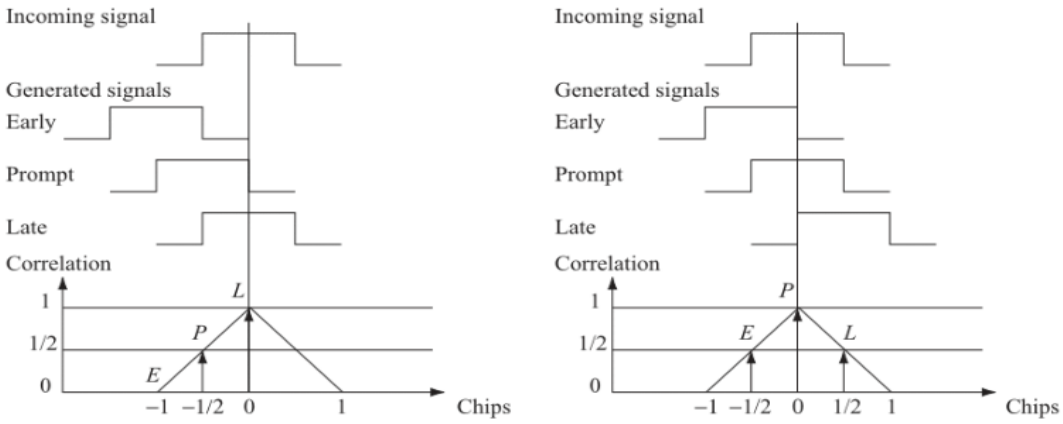


Figure 3.10 Correlators [5]

By looking at Figure 3.10, the relationship between the three correlators can easily be understood. The time difference between the three correlators are one chip as illustrated.

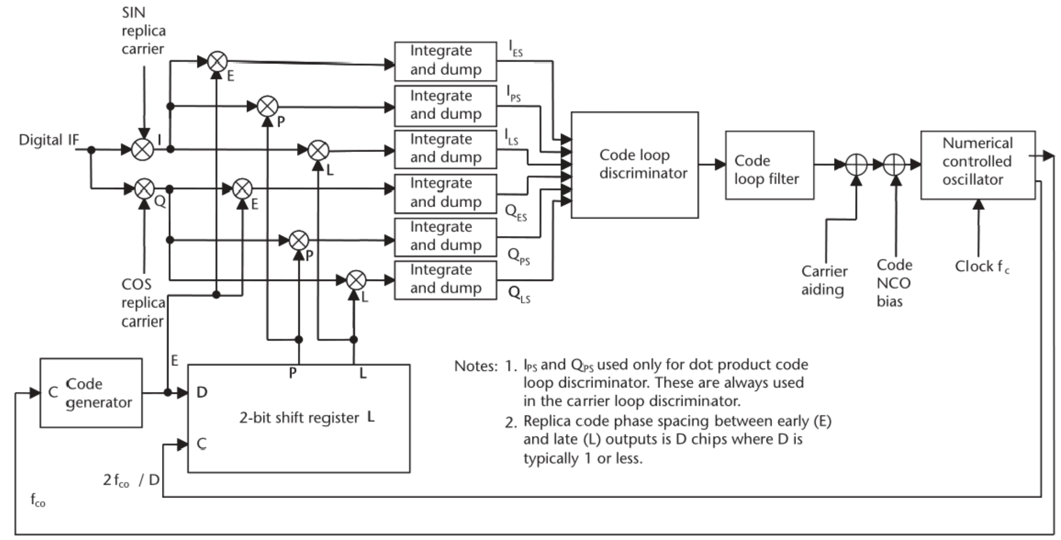


Figure 3.11 Code tracking loop [6]

Figure 3.11 describes the code tracking loop. The prompt, late and early correlators are multiplied with the in phase and quadrature component of the incoming signal. The in phase and quadrature components are obtained from carrier wipe-off process at carrier tracking block. The result of the multiplication gives six results. These results are inputs of the code loop discriminator. The code loop discriminator outputs the error which is the time difference between prompt correlator and incoming signal. The error term is filtered by code loop filter. The result drives the numerically controlled oscillator which adjusts dynamically the code frequency in order to track the incoming C/A code signal. Alternatively, the code tracking loop can be fed by external aids such as carrier aiding. Carrier aiding works with the idea by using the carrier frequency, while the code frequency can be estimated. This technique is more valuable for tracking the code frequency under high dynamic environments.

3.5.3 Discriminators

This subject is described in detail in [6] and [8]. The discriminators simply calculate the tracking error term between the incoming signal and locally generated signal. There are three types of discriminators. The first one is Phase Locked Loop discriminator. This type of discriminator is used for detecting the phase difference between the incoming carrier signal and locally produced signal. The second one is Frequency Locked Loop. This type of discriminator is used for calculating the frequency difference between the incoming carrier signals and locally produced one. The last one is the Delay Locked Loop which is used for sensing the time difference between the incoming C/A code signal and locally produced C/A code signal. The PLL and DLL will be described in the following sections.

3.5.3.1 DLL Discriminator

As mentioned before, the Delay Lock Loop computes the time error between incoming C/A code and replica code. By using the output of DLL, NCO is updated for producing desired output frequency.

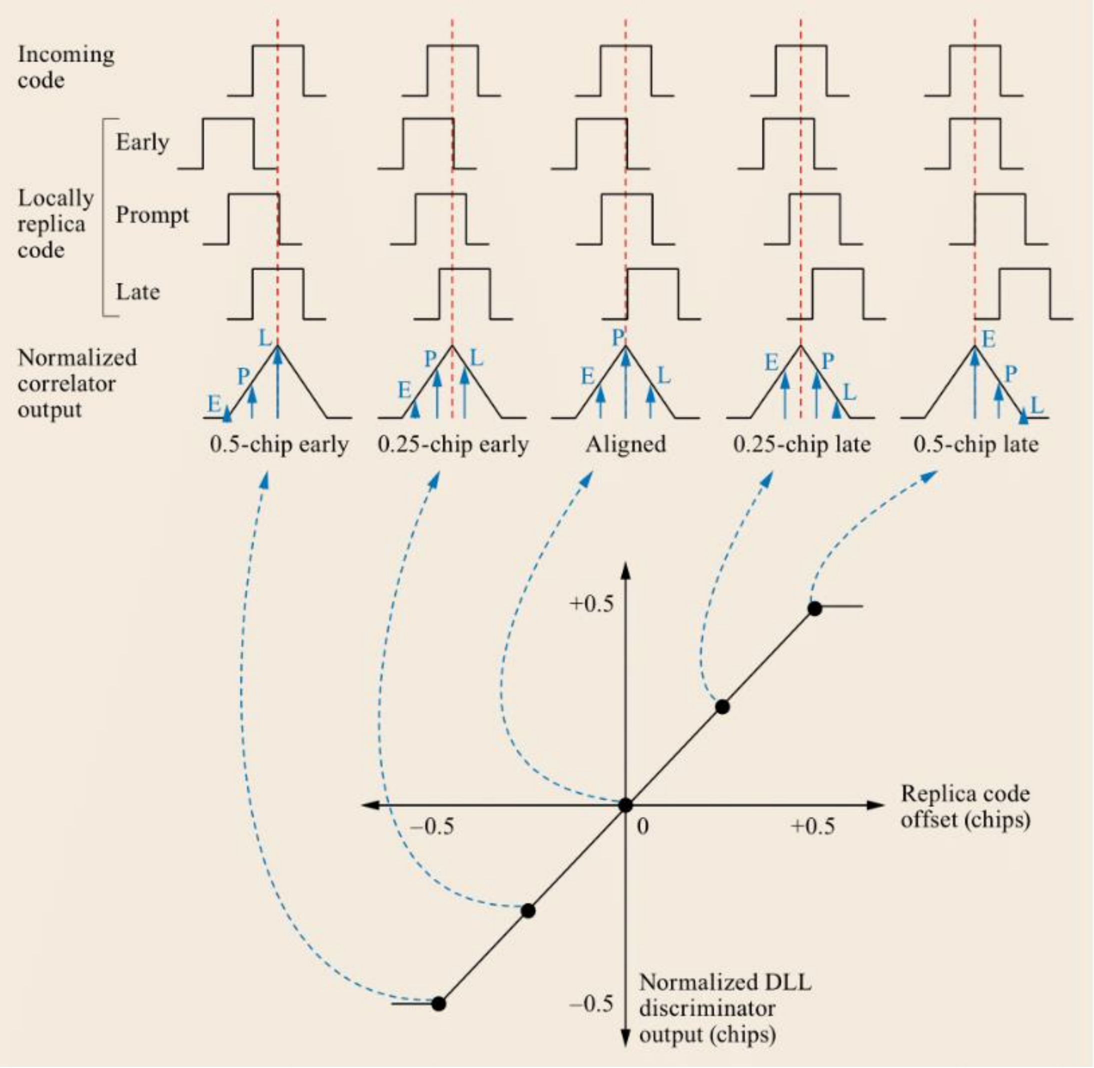


Figure 3.12 DLL discriminator [8]

As illustrated in Figure 3.12, the aim of the tracking loop is to align the prompt code with the incoming code. To achieve this aim, the DLL discriminator computes the replica code offset in chips by using the computing early and late power of the tracking loop.

$$\Delta t = 0.5\frac{(E-L)}{(E+L)} \quad (\mathbf{3.1})$$

There are lots of discriminators which are used to calculate the time error, in equation 3.1 one of them is described. E is the early power which comes from early prompt code tracking loop, L is the late power which comes from late prompt code tracking loop. Figure 3.12 describes the fact that the time difference between the prompt correlator and the incoming code determines the DLL discriminator error, and this error is calculated by using early and late correlators.

3.5.3.2 PLL Discriminators

The Phase Lock Loop computes the phase difference between the replica carrier and incoming carrier signal. To calculate this error, different discriminators have been presented.

$$\emptyset = \operatorname{atan}\left(\frac{Q}{I}\right) \tag{3.2}$$

In equation 3.2, one of the presented discriminators is described. Q is the prompt correlator’s quadrature part and I is the prompt correlator’s in phase part. By using this formula, the phase difference can be calculated. Since the phase of the incoming carrier signal is changed with data portion of the signal, the discriminator should tolerate this phase alteration. The phase alteration of the incoming carrier signal is 180 degrees at data modulation. Costas loops are insensitive to this type of phase alteration. Equation 3.2 is the only Costas discriminator in the PLL discriminators.

CHAPTER 4

FFT SIZE OPTIMIZED ACQUISITION METHOD

In this study, FPGA based GPS L1 C/A receiver is implemented. The acquisition and tracking tasks are shared between FPGA and microprocessors. The resource consumption of FPGA is the critical point while designing FPGA based receiver. If resource consumption of FPGA increases, then, the power used by the receiver and the heat which the receiver produces will also increase. Additionally, the amount of heat has negative effect on the receiver tracking performance [8]. Also, if the tracking channels and acquisition block of FPGA based GPS receiver use more resources, this means that there is not enough space for new tracking channels. Because of these reasons mentioned above, the resource consumption is critical at FPGA based GPS receivers. Therefore, resource consumption analysis should be taken into consideration.

In this study, the implemented acquisition block is Parallel Code Phase Search Acquisition. The idea behind this method is given at section 3.3.3. The main blocks of this method are local carrier generator, PRN code generator, multiplication, finding magnitude, FFT and inverse FFT. FFT blocks consume more FPGA resources than the other blocks since the data which is used by FFT blocks is buffered. Additionally, since there are 3 FFT blocks in this method, the resource consumption is multiplied by 3 also. Therefore, the resource consumption optimization should be done in FFT blocks. Figure 4.1 and Table 4.1 show the real acquisition results of the gathered two bit raw GPS data by using the software GPS receiver of [5]. The data used in these figures is sampled at 32.768 MHz and the IF frequency is 4.095 MHz. The methods for FFT optimization are given in the following sections.

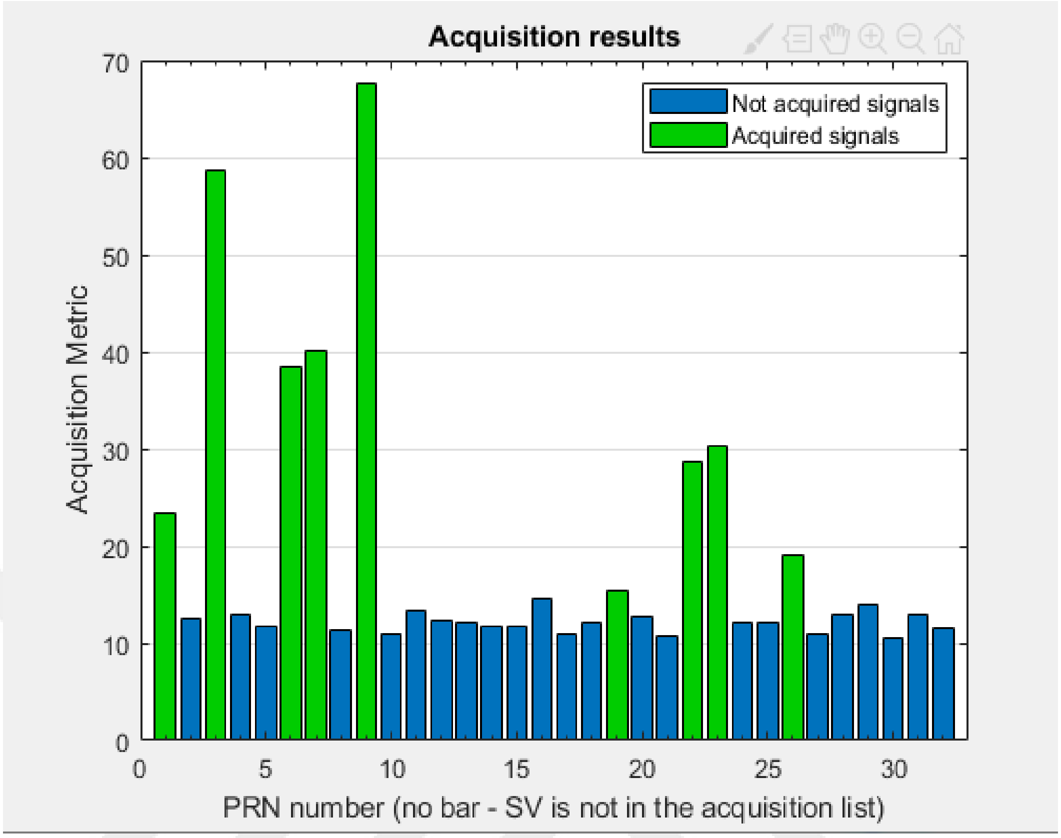


Figure 4.1 Acquisition results

Table 4.1 Detailed acquisition results

Channel	PRN	Frequency	Doppler	Code Offset	Status
1	**9**	**4.0960e6**	**1000**	**19963**	**T**
2	**3**	**4.0930e6**	**-2000**	**15556**	**T**
3	**7**	**4.0980e6**	**3000**	**29880**	**T**
4	**6**	**4.0960e6**	**1000**	**20444**	**T**
5	**23**	**4.0950e6**	**0**	**5191**	**T**
6	**22**	**4.0925e6**	**-2500**	**21708**	**T**
7	**1**	**4.0910e6**	**-4000**	**19023**	**T**
8	**26**	**4.0945e6**	**-500**	**16135**	**T**
9	**19**	**4.0970e6**	**2000**	**12291**	**T**

4.1. Direct Down Sampling of Data

FFT size can be decreased by means of the down sampling of sampling data. However, if this down sampling method is preferred, then, the minimum obtained sampling frequency after down conversion must be two times IF plus Doppler frequency since Nyquist theorem.

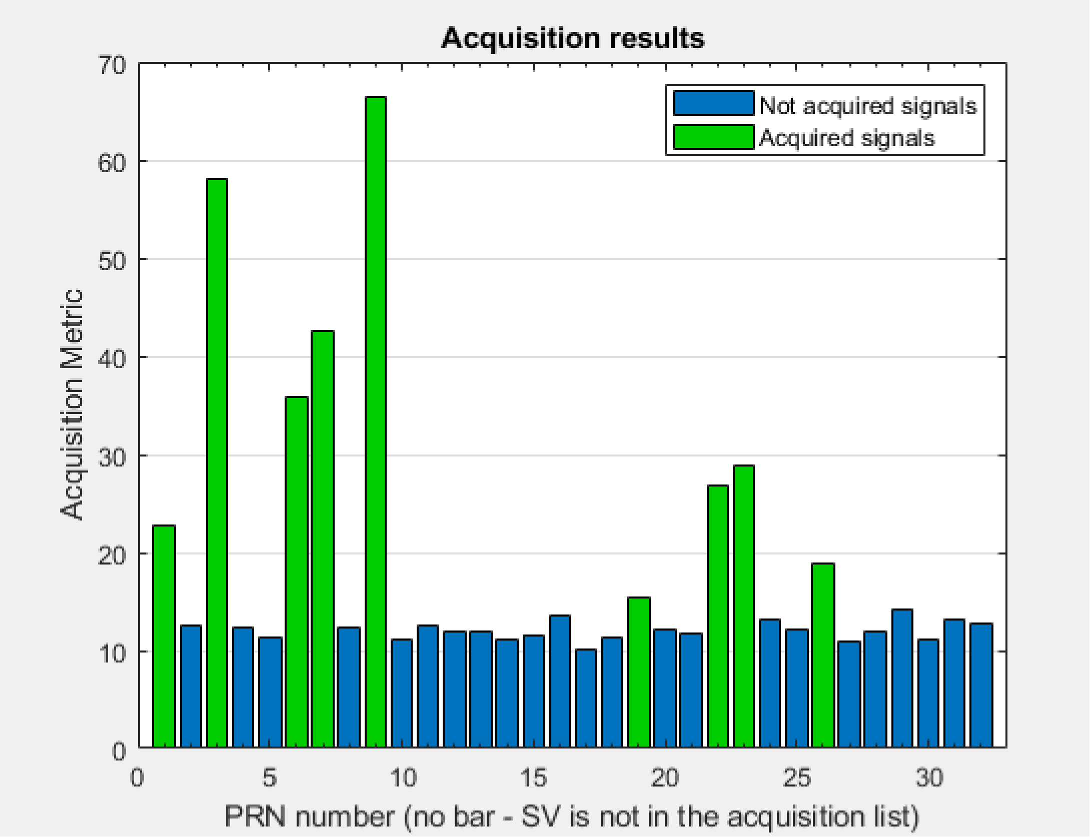


Figure 4.2 Acquisition results down sampling rate 2

Table 4.2 Detailed acquisition results down sampling rate 2

Channel	PRN	Frequency	Doppler	Code Offset	Status
1	**9**	**4.0960e6**	**1000**	**19964**	**T**
2	**3**	**4.0930e6**	**-2000**	**15556**	**T**
3	**7**	**4.0980e6**	**3000**	**29880**	**T**
4	**6**	**4.0960e6**	**1000**	**20444**	**T**
5	**23**	**4.0950e6**	**0**	**5194**	**T**
6	**22**	**4.0925e6**	**-2500**	**21708**	**T**
7	**1**	**4.0910e6**	**-4000**	**19022**	**T**
8	**26**	**4.0945e6**	**-500**	**16138**	**T**
9	**19**	**4.0970e6**	**2000**	**12292**	**T**

In Figure 4.2 and Table 4.2, the sampled data is down sampled at factor 2. This means that at every two data sample, one of them is discarded. As shown in Figure 4.2 and Table 4.2, the acquired satellites are same with the method without down sampling, and also the calculated maximum peaks are similar. However, the calculated code offsets have different values at specific satellites. This is an expected result because down sampling process lost the code offset information slightly. The critical point is that the calculated code offset should not exceed the true offset value half chip length [5]. As shown in Figure 4.2 and Table 4.2, the amount of difference between the true offset value and the calculated offset value does not exceed half chip length.

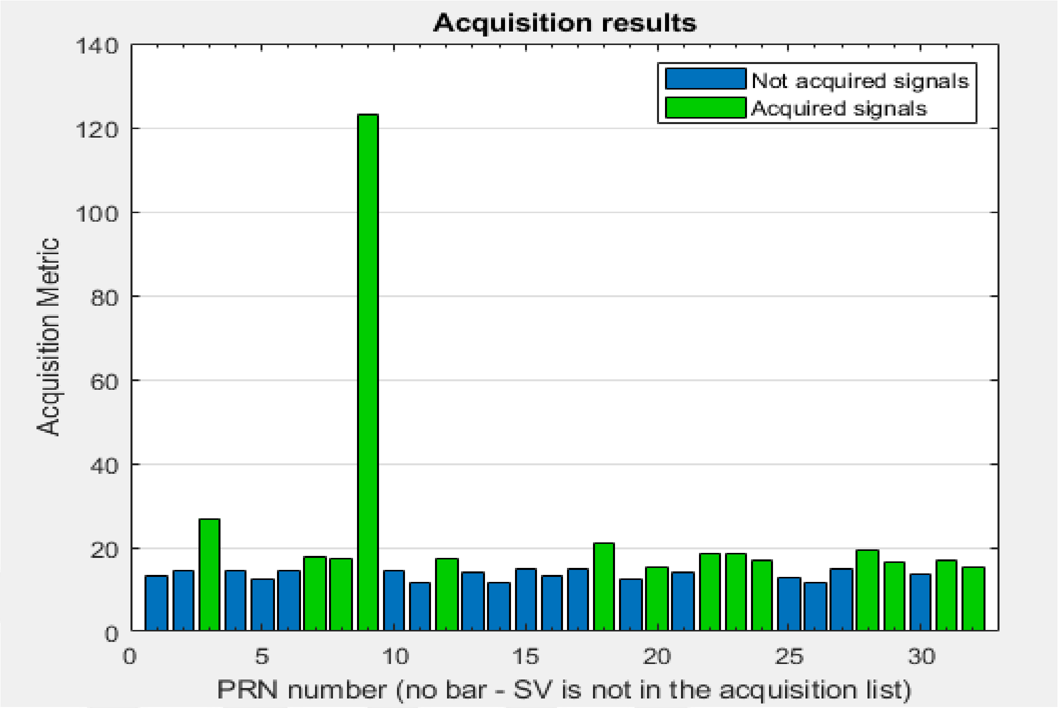


Figure 4.3 Acquisition results down sampling rate 4

Figure 4.3 shows the fact that sampling rate cannot be down converted to Nyquist rate. Since the down sampling rate is 4, then, the sampling frequency is 8.192 Mhz. As expected in this scenario, acquisition process cannot manage to succeed in acquiring the satellites in view.

4.2. Down Sampling of Data after Carrier Wipe-Off

By using direct down conversion method, FFT size can be decreased to a certain amount. The other considered method is that down conversion process can be applied after carrier wipe off process. The idea behind this method is to decrease the FFT size more than direct down conversion method. The carrier frequency of the incoming signal can be decreased also, however, the intermediate frequency should be considered carefully. While working with desired level intermediate frequency, the FFT size can be decreased by using down conversion after carrier wipe off process. Since after carrier wipe off process, the resultant signal has only Doppler frequency, theoretically, the FFT size can be decreased at 1024 point as well.

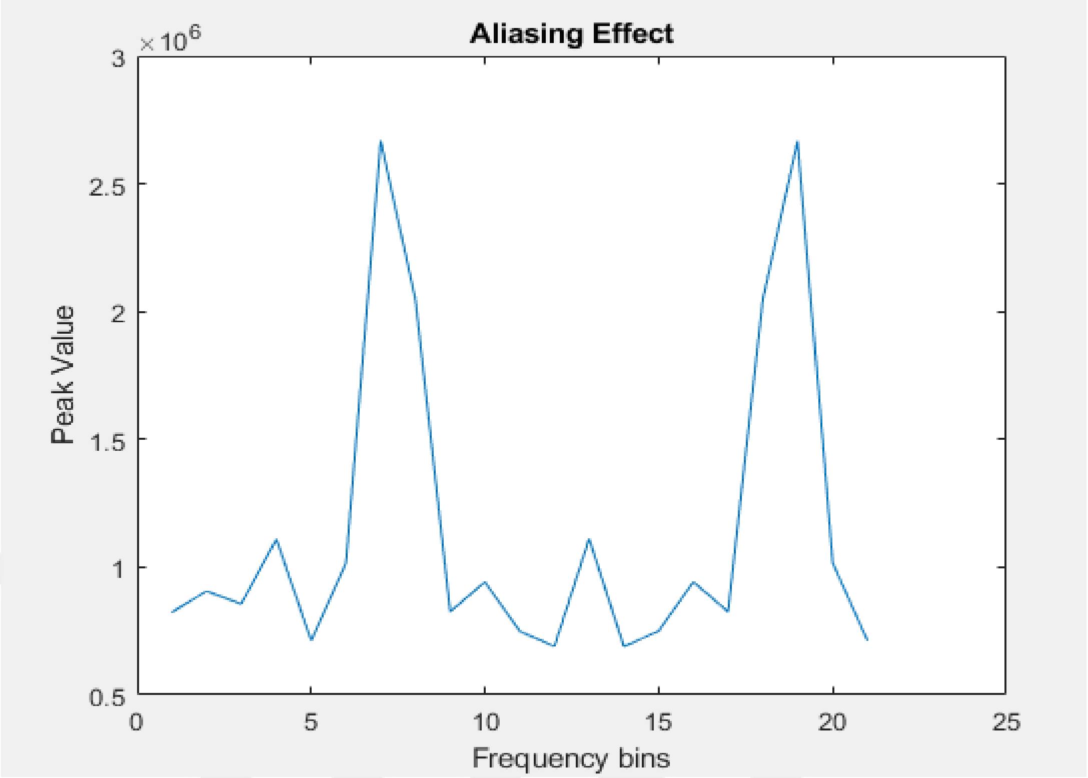


Figure 4.4 Aliasing effect

In Figure 4.4 aliasing effect is illustrated. In Figure 4.4 maximum peak values are shown for each frequency bins for third satellite. It is clear that there are two peak values which are similar to each other. This result is also expected.

$$s_k(n) = \mathrm{C_k(n)D_k(n)cos(2\pi(f_{if} + f_d)n\ )cos(2\pi f_{if}n)}$$

$$= 0.5\ \mathrm{C_k(n)D_k(n)cos(2\pi f_d n)}$$

$$+0.5\mathrm{cos(2w_{if}n)C_k(n)D_k(n)cos(2\pi(2f_{if} + f_d)n\ )} \qquad \mathbf{(4.1)}$$

Equation 4.1 showed that after carrier wipe off process, there are two terms occurred. The first one has only Doppler frequency component, on the other hand, the second term has two times intermediate frequency plus Doppler frequency component. This term must be filtered otherwise as Figure 4.4 shows, aliasing effect occurred since after down sampling, and the sampling frequency is decreased. Therefore, a filter should be designed and implemented after carrier wipe off.

4.3. Down Sampling of Data after Carrier Wipe Off with Filter

In this method, after carrier wipe off process a band pass filter is applied to resultant signal.

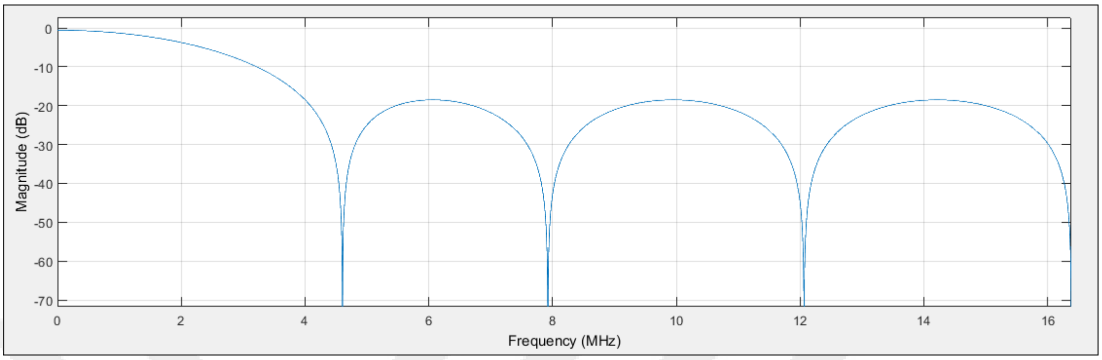


Figure 4.5 Band pass filter

In Figure 4.5, the frequency characteristics of the designed band pass filter is illustrated. The band pass filter is designed to overcome aliasing effect illustrated in chapter 4.2. Since the intermediate frequency is 4.095 Mhz, the double intermediate frequency which leads to aliasing is filtered by designed band pass filter. In this method, after carrier wipe off process, the resultant signal is filtered, then, down conversion is applied. Lastly, the remaining parts of the FFT based acquisition process are performed.

Table 4.3 Detailed acquisition results down sampling rate 2

Channel	PRN	Frequency	Doppler	Code Offset	Status
1	9	4.0960e6	1000	19966	T
2	3	4.0930e6	-2000	15560	T
3	7	4.0980e6	3000	29882	T
4	6	4.0960e6	1000	20446	T
5	23	4.0950e6	0	5196	T
6	22	4.0925e6	-2500	21712	T
7	1	4.0910e6	-4000	19026	T
8	26	4.0945e6	-500	16138	T
9	19	4.0970e6	2000	12294	T

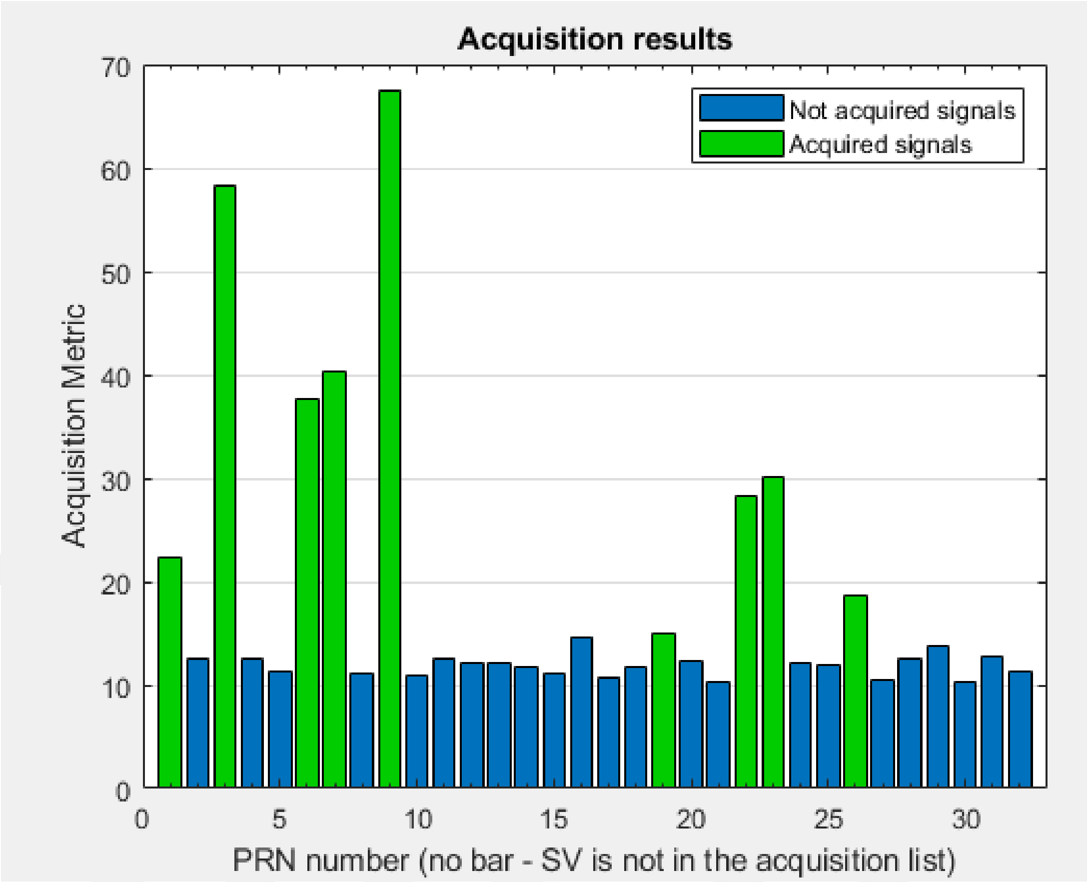


Figure 4.6 Acquisition results down sampling rate 2

Table 4.4 Detailed acquisition results down sampling rate 4

Channel	PRN	Frequency	Doppler	Code Offset	Status
1	**9**	**4.0960e6**	**1000**	**19968**	**T**
2	**3**	**4.0930e6**	**-2000**	**15560**	**T**
3	**7**	**4.0980e6**	**3000**	**29884**	**T**
4	**6**	**4.0960e6**	**1000**	**20448**	**T**
5	**23**	**4.0950e6**	**0**	**5196**	**T**
6	**22**	**4.0925e6**	**-2500**	**21712**	**T**
7	**1**	**4.0910e6**	**-4000**	**19028**	**T**
8	**26**	**4.0945e6**	**-500**	**16140**	**T**
9	**19**	**4.0970e6**	**2000**	**12292**	**T**

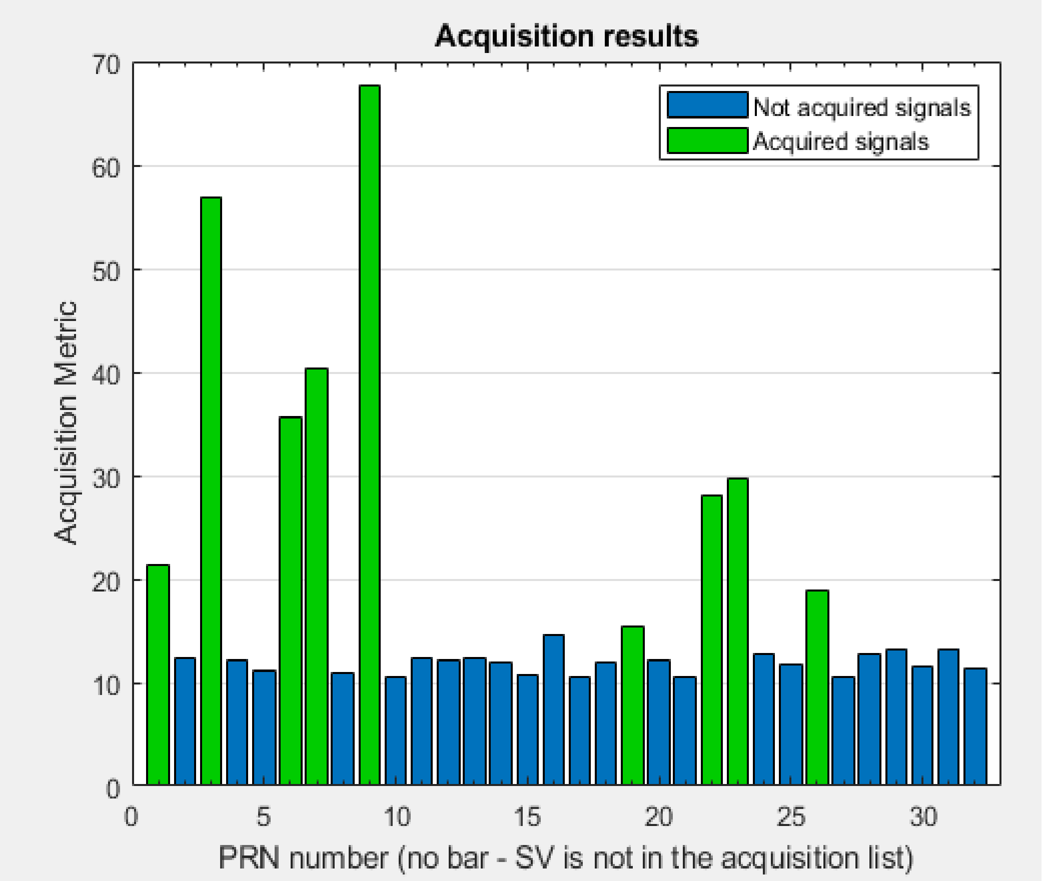


Figure 4.7 Acquisition results down sampling rate 4

Table 4.5 Detailed acquisition results down sampling rate 8

Channel	PRN	Frequency	Doppler	Code Offset	Status
1	**9**	**4.0960e6**	**1000**	**19968**	**T**
2	**3**	**4.0930e6**	**-2000**	**15560**	**T**
3	**7**	**4.0980e6**	**3000**	**29880**	**T**
4	**6**	**4.0960e6**	**1000**	**20448**	**T**
5	**22**	**4.0925e6**	**-2500**	**21712**	**T**
6	**23**	**4.095e6**	**0**	**5192**	**T**
7	**1**	**4.0910e6**	**-4000**	**19024**	**T**
8	**26**	**4.0945e6**	**-500**	**16136**	**T**
9	**-**	**-**	**-**	**-**	**Off**

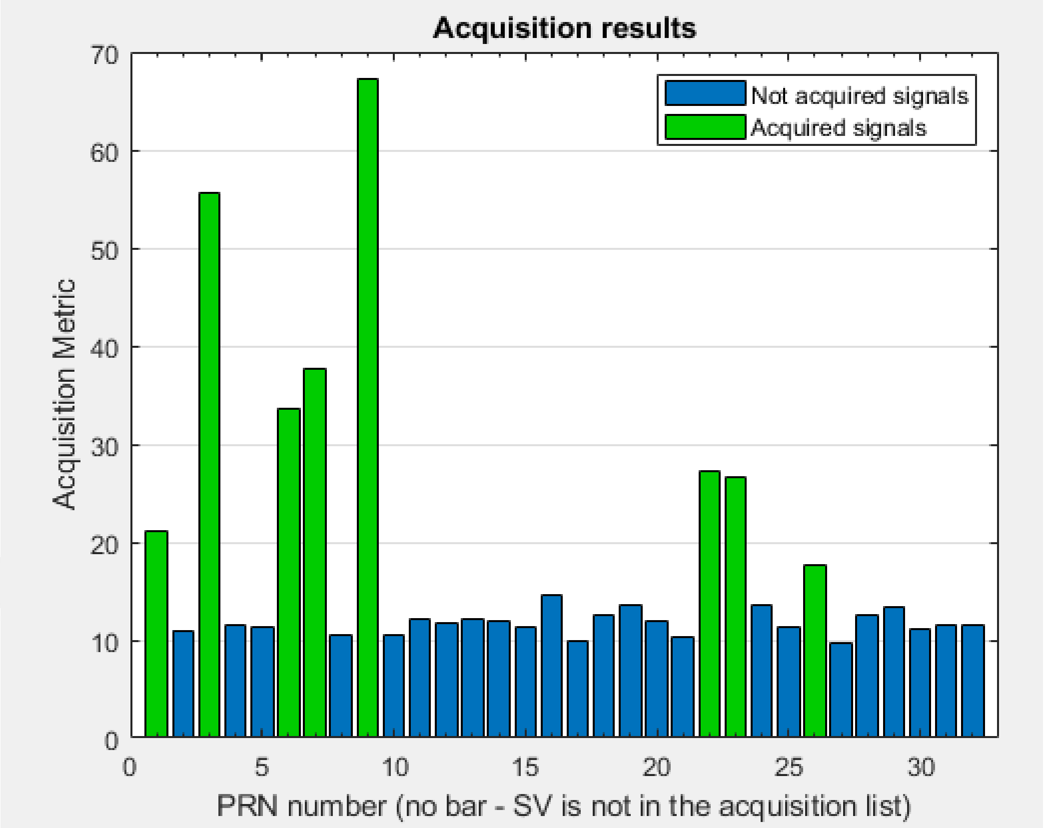


Figure 4.8 Acquisition results down sampling rate 8

Table 4.6 Detailed acquisition results down sampling rate 16

Channel	PRN	Frequency	Doppler	Code Offset	Status
1	**9**	**4.0960e6**	**1000**	**19968**	**T**
2	**3**	**4.0935e6**	**-1500**	**15552**	**T**
3	**6**	**4.0960e6**	**1000**	**20448**	**T**
4	**7**	**4.0980e6**	**3000**	**29888**	**T**
5	**22**	**4.0925e6**	**-2500**	**21712**	**T**
6	**23**	**4.0950e6**	**0**	**5200**	**T**
7	**1**	**4.0910e6**	**-4000**	**19024**	**T**
8	**31**	**4.0915e6**	**-3500**	**31632**	**T**
9	**-**	**-**	**-**	**-**	**Off**

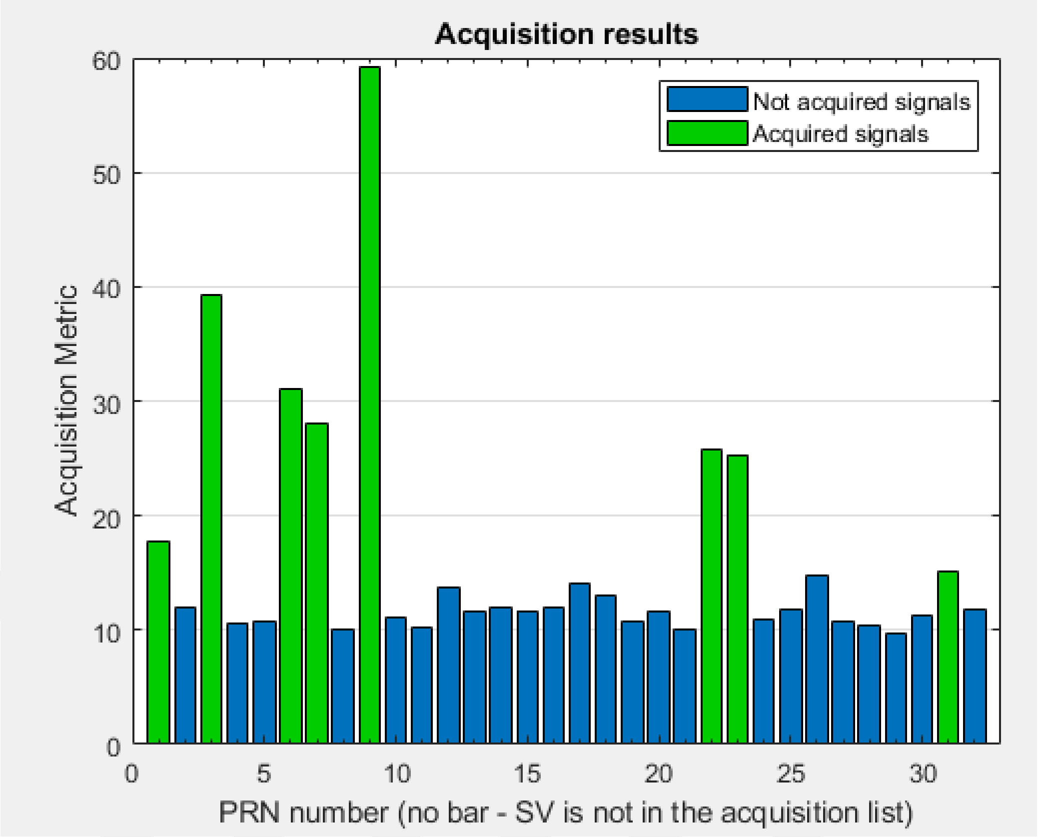


Figure 4.9 Acquisition results down sampling rate 16

Table 4.7 Detailed acquisition results down sampling rate 32

Channel	PRN	Frequency	Doppler	Code Offset	Status
1	**9**	**4.0960e6**	**1000**	**19968**	**T**
2	**3**	**4.0930e6**	**-2000**	**15552**	**T**
3	**6**	**4.0960e6**	**1000**	**20448**	**T**
4	**8**	**4.0925e6**	**-2500**	**14496**	**T**
5	**7**	**4.0980e6**	**3000**	**29888**	**T**
6	**-**	**-**	**-**	**-**	**Off**
7	**-**	**-**	**-**	**-**	**Off**
8	**-**	**-**	**-**	**-**	**Off**
9	**-**	**-**	**-**	**-**	**Off**

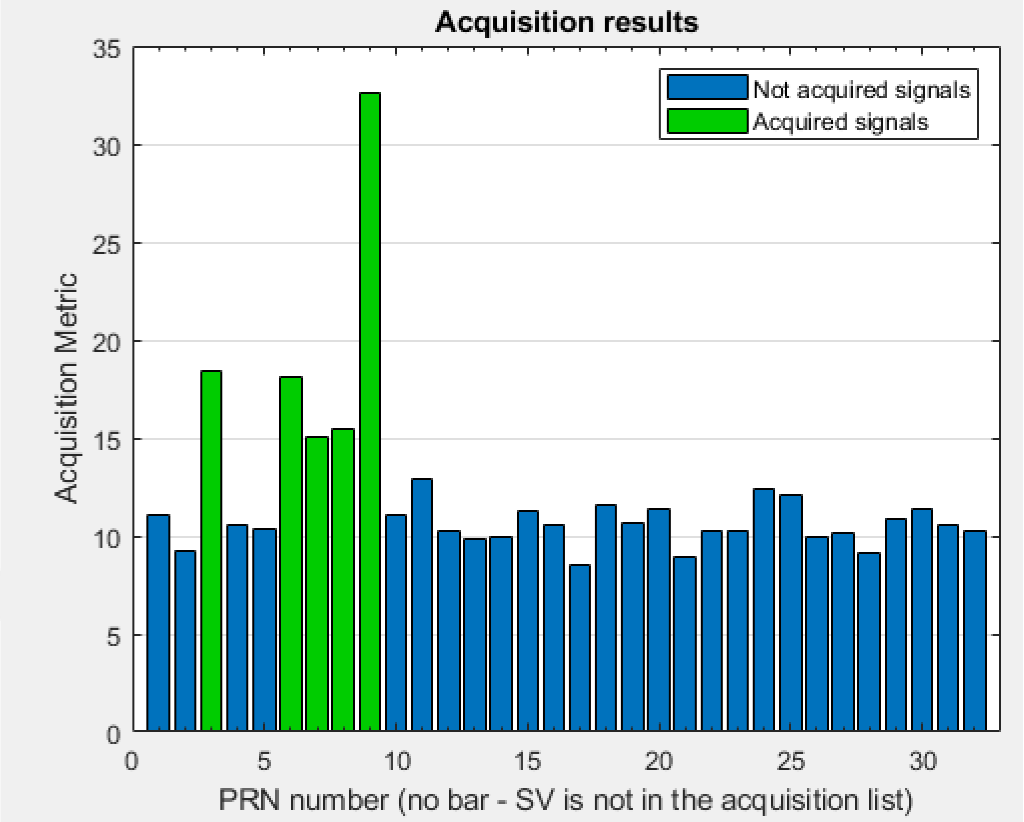


Figure 4.10 Acquisition results down sampling rate 32

The acquisition results are shown between Figure 4.6 and Figure 4.10 for different down sampling rates. The results show that if down sampling rate is increased, the difference between the calculated code offset and true code offset is increased for some satellites in view. However, the critical point is that the difference between the true code offset and calculated code offset should not be over the half chip length. The half chip is 16 samples at 32.768 MHz sampling frequency. The detailed acquisition results show that the code offset difference is not bigger than 16 samples. The Doppler frequency difference between the true value and the calculated frequency should not be over 500 Hz. The detailed acquisition results show that the difference Doppler frequency between the true frequency and calculated value is not over 500Hz. On the other hand, some of the satellites in view cannot be detected by acquisition process for specific down sampling rates. Furthermore, some satellites which are not in the receiver’s view are acquired. These results are expected since there is information lost for increasing down sampling rates. Since the acquisition is a continuous process when the GPS receiver is power on, the undetected satellites can be acquired in next raw GPS samples. Since the tracking process is performed after acquisition, the satellites acquired which are not in view of the GPS receiver can be dropped from tracking channels.

CHAPTER 5

CONCLUSION

In this work, the acquisition and tracking blocks of an SDR based GPS receiver is discussed. The different ways of the acquisition are explained and the comparison between these ways are shown. The features of GPS L1 C/A code are clarified. The mathematical operations in the acquisition and tracking blocks are identified. Inputs and outputs of the tracking and acquisition blocks are clearly explained. The Doppler frequency and code phase offset is described. The tracking mechanism of the GPS L1 C/A signal is explained and main parts of the mechanism are identified. Also, a new method which optimizes the computational complexity of an FFT based acquisition block is proposed. The implementation results about this method are given.

There are some future works about the optimization method on acquisition process. First of all, the calculated code phase for low elevation satellites which have lower signal quality is far away from half chip length for down sampling frequency below 2 Mhz. This leads to losing the signal track in the tracking process. In tracking process, the tracking loop can be initiated with frequency lock loop for specific time. After the frequency and code phase error are lower than specific threshold value phase lock loop can be used instead of frequency lock loop. Secondly, under interference condition the received signal quality will be degraded. This leads to poor acquisition and tracking performance. This optimization method is not tested with interference condition. Lastly, in the high dynamic environment which is the GPS receiver has high acceleration and acceleration rate, the Doppler frequency changes so rapidly. The code phase and frequency error increase largely in small amount of time. The tracking and acquisition processes are challenging under this environment. The optimization method should be tested in the high dynamic environment.

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