PRN Code Correlation in GPS Receiver

Ahmet Esat SÜZER, Hakan OKTAL
Department of Avionics, Faculty of Aeronautics and Astronautics,
Anadolu University, Eskisehir, Turkey
ahmetesatsuzer@anadolu.edu.tr, hoktal@anadolu.edu.tr

Abstract*— Satellite based positioning systems like GPS (Global Positioning System) exist in every moment of our lives. GPS signal is broadcasted by Link1 (L1) and Link2 (L2) frequencies, separately. L1 is assigned to civil users, while L2 is especially for military users. GPS signal consists of navigation message and PRN codes (C/A for civil and P-code for military) which is an identity for satellite. PRN codes are also used to determine the range between the satellite and the receiver. The navigation message added on PRN code, must be known to find the position of GPS receiver on Earth. Identification of PRN code is the most important process to calculate the receiver's position. A correlation process in receiver is implemented to find PRN code changing for each satellite. Three common methods are available for the correlation process. These methods are Serial Search, Parallel Frequency Space Search and Parallel Code Phase Search Acquisition. Parallel Code Phase Search is faster and ended in less steps compared to other two methods. The aim of this study is to present the correlation technics used for the acquisition of satellite signal in GPS receivers. For this purpose, a correlation example is simulated in MATLAB environment to demonstrate how the correlation process in GPS receiver is performed.

***Keywords*—GPS signal; correlation; PRN code; acqusition; matlab**

I. Introduction

GPS is a satellite system which provides position, time and velocity informations. The system was initially designed as 24 satellites in 6 orbits [1]. But actually, GPS contains 31 operational satellites, which are 12 Block IIR, 7 Block IIR (M) and 12 Block IIF. The GPS project revealed by United State of America (USA) was approved in 1973. The first satellite was launched in 1978. In August 1993, GPS had 24 satellites in orbit and in December of the same year the initial operational capability was established. In February 1994, the Federal Aviation Agency (FAA) declared GPS ready for aviation use [1, 2, 3]. GPS signal is broadcasted in Link1 (L1) and Link2 (L2) frequency bands, which are assigned to civil and military users. L1 (1575.42 MHz.) and L2 (1227.60 MHz.) signals are generated from the fundamental frequency 10.23 MHz. by multiplying with 150 and 120 respectively.

In general, a GPS signal includes Pseudo Random Noise (PRN) code or ranging code and navigation message. PRN code seems to be random however in fact it is generated using shift registers by a known algorithm or rule. PRN codes is derived for each satellite by selecting different pairs of cells from each register to define register output [4]. Therefore all PRN codes are precisely defined and each satellite has a unique PRN code, numbered 1 to 37. For example, PRN 1 is assigned to satellite 1 or PRN 21 is assigned to satellite 21. It is used for some important purposes. It allows any receiver to identify exactly which satellite signal it receives and also is used to calculate distance between the satellite and receiver. There are two different PRN code for legacy GPS. One of them is Coarse/Acquisition Code (C/A) for civil applications, another one is Precision Code (P-Code) for military applications. Transmitted signals on the L1 frequency band consist of C/A and P codes and navigation message. While the C/A code is broadcasted on only L1, P-Code is broadcasted on both L1 and L2. C/A code repeats every 1 millisecond and its length is 1023 bits. Due to the fact that C/A code repeats 1000 times per second, data transmission speed is 1.023 Mbps for C/A code. Just as C/A code, P-code is generated from shift registers as well. It only repeats every 37 weeks and its length is 2×10^{14} bits. P-code period of each satellite is allocated as any week of the 37 weeks period. Its transmission speed is 10.23 Mbps. which is ten times greater than the transmission speed of C/A code. Therefore the range measurements between the satellite and receiver are performed ten times more accurately with P-code. Along with the PRN code on L1 and L2 frequencies, the navigation message which contains the data to calculate position, velocity and time is modulated on top of both the C/A and P ranging codes at 50 bit/s.

The complete navigation message consists of 25 frames and the duration of each frame is 30 seconds. The frames are formed by five sub-frames with 300 bits each [2, 3, 5]. A sub-frame contains 10 words with 30 bits length and duration of a word is 0.6 second. Each sub-frame routinely starts respectively with telemetry word (TLM) and handover word (HOW). TLM is used to detect the beginning of a sub-frame by using fixed 8 bits preamble sequence. HOW is second word in each sub-frame and following TLM word. HOW provides the GPS time-of-week (TOW) modulo 6 seconds corresponding to the leading edge of the following sub-frame and sub-frame ID. The HOW also provides two flag bits, one that indicates whether anti-spoofing is activated [1]. Sub-frame 1 consists of parameters like satellite clock, health status, week number, satellite clock correction. Sub-frame 2 and 3 include satellite ephemeris data which contains very accurate information about the satellite's orbital parameters, position and velocity [3, 5]. Ephemeris data can be valid up to several hours. . Sub-frame 4 comprises of almanac data for satellites among 25-32, ionospheric correction data, Universal Time Coordinated (UTC), health information for satellites among 25-32. Sub-frame 5 consists of almanac data for

978-1-5386-1605-5/17/$31.00 ©2017 IEEE

satellites among 1-24, health information for satellites among 1-24, almanac reference time and almanac reference week number [5]. Almanac data contains the status and the orbital parameters of all satellites and it also helps to find the satellite that the received signal comes [1]. When it is compared with ephemeris, almanac data are not so precise and is valid up to several months. Each satellite broadcasts only its own ephemeris data whereas every satellite broadcasts almanac data for available satellites in orbit.

GPS signal with PRN code and navigation message is transmitted by using Binary Phase Shift Keying (BPSK) modulation technique. BPSK is a digital modulation in which a carrier is either transmitted with 0º or 180º phase shift as dependent on whether 0 or 1 is transmitted. Fig. 1, shows an example of how to modulate a GPS signal for civil and military users. For the civil users, the navigation message is added on the C/A code of the satellite by using XOR logic gates and then the resultant signal is mixed with L1 frequency carrier wave by BPSK technique and finally obtained signal is broadcasted for receivers by the satellite.

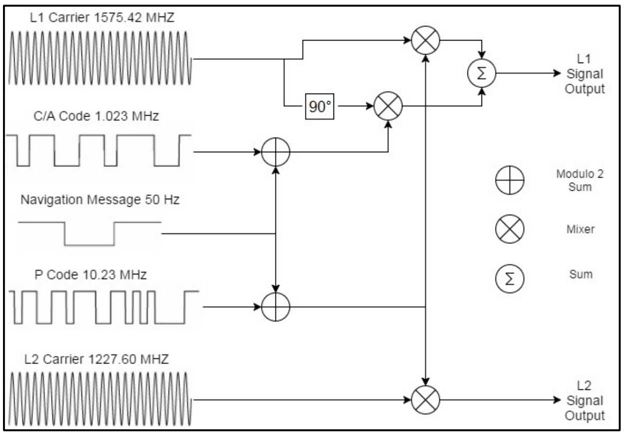


Fig. 1. GPS signal modulation [6]

The most crucial and difficult stage in GPS receiver's positioning process is to catch the PRN code of the satellite. Additionally, environmental noise and Doppler frequency shift resulting from the satellite movement make difficult the signal acquisition. The aim of this study is to present the general receiver structure and the correlation technics used for the acquisition of the satellite signal and its PRN code. In this framework, three different acquisition technics used in GPS receivers are explained and a serial search method, one of the acquisition technics, is simulated in MATLAB as an example to demonstrate the importance of correlation process. Finally, the simulation results are discussed.

II. RECEIVER STRUCTURE

A. General GPS Receiver Blogs

As seen in Fig. 2, a GPS receiver consists of several fundamental components: an antenna with preamplifier and prefiltering, a radio-frequency and intermediate frequency (RF/IF) front end section, baseband processing section for correlation [2, 7, 8]. An RF signal from a GPS satellite is received via antenna. Incoming signal is very weak because of the travel distance and the distortion effects such as noise and undesired signals. Therefore, in antenna section, the incoming signal is amplified with low-noise amplifier (LNA) or preamplifier and removed from external effects by means of prefiltering. In front end section, RF is converted to Intermediate Frequency (IF) which is lower frequency to process the signal easier. Down conversion block is used for RF to IF conversion. It utilizes a local oscillator which is pure sinusoidal wave and known frequency. Down conversion accomplishes by mixing local oscillator and incoming signal [7]. The mixing process creates both lower and upper sidebands. However, the lower sideband is filtered by a band pass filter. Then the obtained analog signal is converted into a digital signal by means of analog-to-digital converter (ADC). The signal processing step is performed in baseband section during acquisition and tracking of the satellite signal.

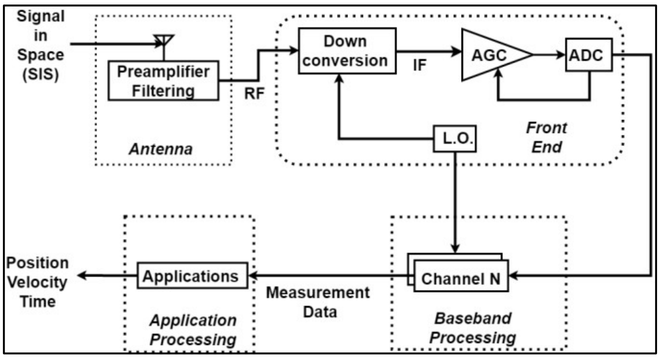


Fig. 2. General receiver block diagram [9]

Baseband section consist of the loop discriminators, filter, data demodulator, SNR meters and phase lock indicators [1]. Acquisition means to find the signal of a visible satellite and determine values of the carrier frequency and code phase of the satellite signals [3, 10]. It exists three different acquisition methods: Serial search, parallel frequency space search and parallel code phase search. Serial search acquisition is an often-used method for acquisition in code division multiple access systems (CDMA) like GPS [10]. In this method, both locally generated PRN code and locally generated carrier wave are used for the process (Fig. 3.). The serial search method uses frequency and code phase sweeps.

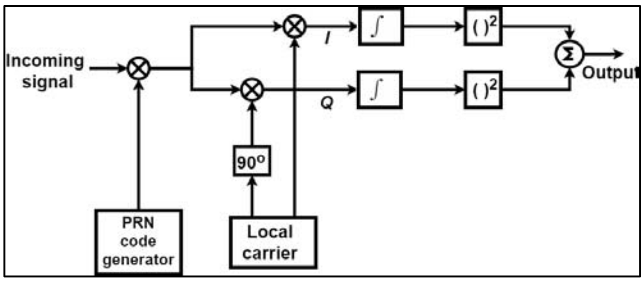


Fig. 3. Serial search acquisition [10]

Since there are many number of combinations to find Doppler shift and code delay, it is quite time-consuming procedure. The Doppler shift is produced by the relative motion of the satellite with respect to the receiver [1]. The Doppler shift can be defined as frequency difference among transmitted signal and the received signal. For instance, maximum Doppler frequency shift for a fixed GPS receiver is approximately ±5 kHz and ±10 kHz for a mobile receiver. In serial search method, the frequency sweep is performed with 500 Hz. intervals (2x10000/500+1=41) and code delay sweep with one chip intervals (1023 chips). The total combination will reach up to 41.943 (41x1023) combinations. Parallel frequency space search method is implemented by using only code phase sweeps and so the performance of method notably increases [10]. This method utilizes local PRN code and the Fourier transform, which transforms signal from time domain to frequency domain (Fig. 4.). After local PRN code is generated and multiplexed by the incoming signal, eventually the resulting signal is transformed into the frequency domain by Fourier transform [10]. When the locally generated PRN code is perfectly aligned with the code in the incoming signal, the output of the Fourier transform will show a distinct peak in magnitude.

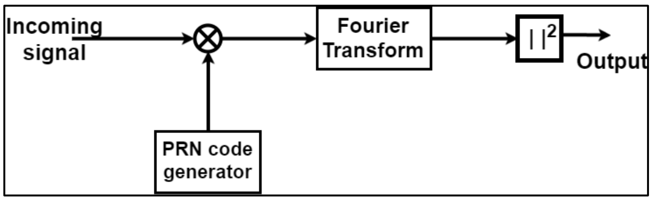


Fig. 4. Parallel frequency space search acquisition [10]

The peak will be located at the frequency of the carrier wave signal [10]. However thanks to the frequency domain transformations, the method is faster compared to the serial search method. On the other hand, the parallel code phase search acquisition uses 41 different carrier frequency without code phases. Instead of multiplying the input signal with a PRN code with 1023 different code phases, it is more useful to make a circular cross correlation between the input and the PRN code without shifted code phase and hence only 41 different carrier frequency steps is performed, as done the parallel code phase search method (Fig. 5.)[10]. Along with this method, correlation process is faster and more accurate.

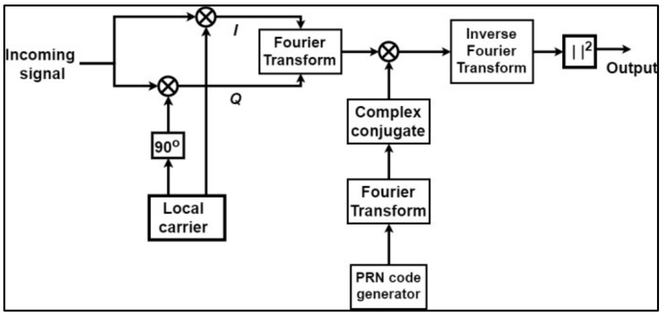


Fig. 5. Parallel code phase search acquisition [10]

The tracking mode is used to find the phase transition of the navigation data [3]. By using the phase transition, it is obtained pseudo-ranges, ephemeris and almanac information.

The receivers have some different channels to process each incoming signal. The main objective in baseband processing is to perform code delay and carrier phase measurements. Thus the GPS signal acquisition and tracking process is a two-dimensional signal replication process as code and carrier [1]. Delay Lock Loop (DLL) is for code delay whereas Phase Lock Loop (PLL) is for phase measurements or phase delay [1]. The signal is eliminated from Doppler frequency shift in this section whereby the correlators. Application processing stage obtains data from each channel of previous stage and merges these data to calculate the position and velocity of the receiver and time.

B. General Theory of PRN Code Correlation

Correlation can be simply defined as similarity between two variables. The main objective in computing the correlation between two signals is to measure the degree to which the two signals are similar. Correlation of signals is often encountered in satellite systems, radar, sonar, digital communications, geology and other areas in science and engineering [11]. There are two kinds of correlation, which are auto correlation and cross correlation functions. Cross-correlation is used to measure similarity between two different signals whereas auto correlation is used to examine relationship which a signal is with itself. Cross-correlation function is mathematically expressed in (1)

$$R_{xy} = \int_{-\infty}^{\infty} x(t)\, y(t+\tau)\, dt \qquad (1)$$

R_{xy} expresses cross-correlation function (CCF), *x (t)* and *y (t)* are any signal, τ is shifted-time. In the same way, auto correlation function is mathematically derived just as below

$$R_{xx} = \int_{-\infty}^{\infty} x(t)\, x(t+\tau)\, dt \qquad (2)$$

R_{xx} denotes auto correlation function (ACF). It can be seen that auto correlation function is derived when *x (t)* is written instead of *y (t)* in (1). Correlation analysis attempts to measure the strength of such relationships between two variables by means of a single number called a correlation coefficient [12, 13]. The correlation coefficient is also known as the product-moment coefficient of correlation or Pearson's correlation. A large, positive correlation coefficient indicates a relation between the signals, while a correlation coefficient close to zero means that the two signals are not (or that they are not lined up properly). A negative number indicates a negative correlation, meaning that one signal tends to decrease as the other increases [14]. Equation (3) shows the correlation coefficient formula

$$\rho = \frac{Cov\,(x, y)}{\sigma_x \sigma_y} \qquad (3)$$

In the equation (3), *Cov* represents covariance, σ denotes standard deviation. The correlation coefficient lies always between -1 and +1. If it is +1 or -1, the correlation between two signals is so strong. If it is approximate to zero, the correlation between two signals is weak and it can be said that two signals are statistically independent. Just as mentioned in introduction section, PRN is as important as navigation message for receivers. It has two crucial tasks. One of these is to determine the satellite that the received signal comes from. Another one is to calculate distance or pseudo-ranges between the receiver and the satellite. One of the most important properties of the PRN codes is their correlation result [10]. Correlation of any two PRN codes from different satellites is low. Auto correlation of any PRN code also is quite low except for zero phase lag, which correlation is high.

To determine C/A code, a correlation operation is performed to the incoming signal. In correlation operation, all possible PRN codes are generated as local replica in the receiver. Then the incoming signal from the satellite is correlated respectively with 37 different PRN codes by shifting the local generated PRN code in receiver. When the phase of the GPS receiver replica code matches the phase of the incoming SV code, there is maximum correlation. When the phase of the replica code is offset by more than 1 chip on either side of the incoming SV code, there is minimum correlation [1]. As a consequent of this process, the C/A code with maximum correlation is determined as satellite number or PRN code. For instance, when it is assumed that C/A code of the incoming signal is PRN 1, the receiver correlates all local generated PRN codes with the incoming signal, as a result of the correlation, PRN 1 will have maximum correlation value when compared to PRN 2, PRN 3 and the others. Ultimately, it is understood that C/A code of the incoming signal is PRN 1 or the signal comes from satellite 1. Then via the PRN 1, navigation message is discriminated from the incoming signal and the position of receiver on Earth is determined. Fig. 6 demonstrates correlation results of any received signal with PRN 5, PRN 10, PRN 20, and PRN 30. Just as seen in Fig. 6, when the incoming signal is respectively correlated by PRN 5, PRN 10, PRN 20 and PRN 30, eventually maximum correlation occurs in PRN 20 (blue color). So, it is figured out that the C/A code of the received signal is PRN 10. In addition to finding satellite number, PRN is also used to calculate distance between receiver and satellite. Travelling or delay time of a radio signal can basically be calculated as the difference between arrival time at the receiver and time of signal transmission. The distance can be calculated through (4).

$$d = c\Delta t \quad (4)$$

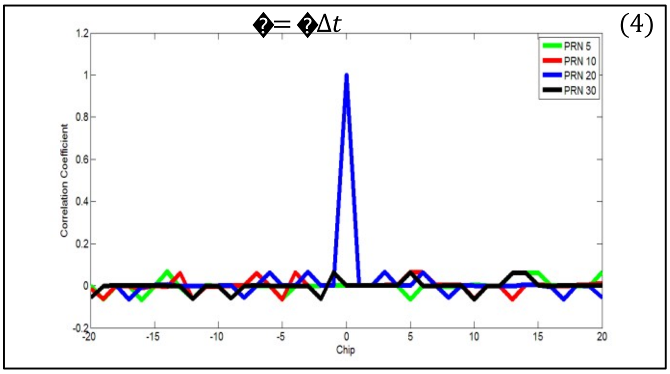


Fig. 6. Different PRN code correlation results

d denotes distance, *c* is the speed of light, which is about $3x10^8$ m/s, and Δt is delay time. Time difference between transmitted and arrival signal is pointed out in Fig. 7.

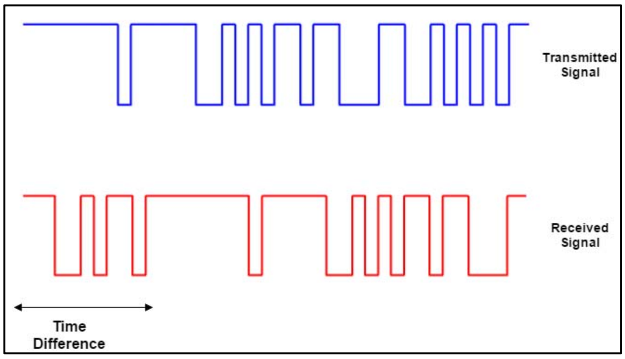
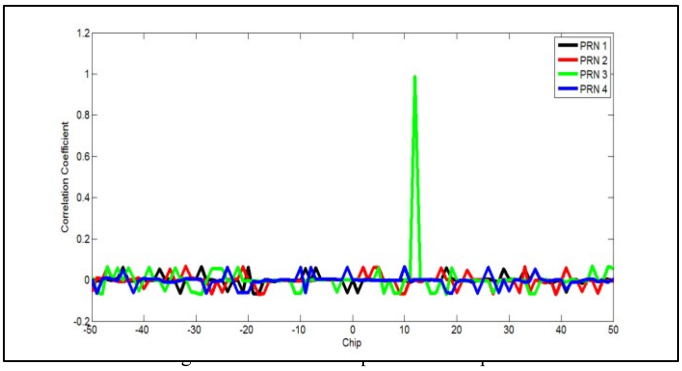


Fig. 7. Time difference between received and transmitted signal

III. Simulation of PRN Code Correlation

In this study, a serial search method as a fundamental example is implemented in MATLAB to determine which satellite the signal comes from and to calculate the distance between the receiver and the satellite. The real PRN codes were generated for the correlation process in MATLAB. The incoming signal was delayed in receiver to create a phase difference between the real and the locally generated codes. Then delayed signal was correlated with local codes PRN 1, PRN 2, PRN 3 and PRN 4 respectively. As depicted in Fig. 8, since the correlation result of the PRN 3 has a peak value, PRN code of the incoming signal is found as PRN 3. After catching the appropriate PRN code, the phase delay used for the calculation of the range between the satellite and the receiver is determined as 12 chips by taking into account 1 chip duration is about 1 micro second. According to this chip delay, the pseudo-ranges can be calculated.



If the signal coming from a satellite did not include noise, Doppler frequency shift and undesired signal, the C/A code could be determined by only a correlation operation. The correlation in practice is the same way but more complex. When the effects of noise, Doppler shift and undesired signals are taken into account, six different correlations are performed simultaneously to remove undesired effects on the signal.

In this framework, after the incoming signal is multiplied with locally generated carrier including sine and cosine signals, in-phase (I) and quadrature phase (Q) signals are produced. As demonstrated in Fig.9, three local codes as Early (E), Late (L) and Prompt (P) for each PRN code are generated. The three local codes are separated with 0.5 chip apart. Early (E) and Late (L)

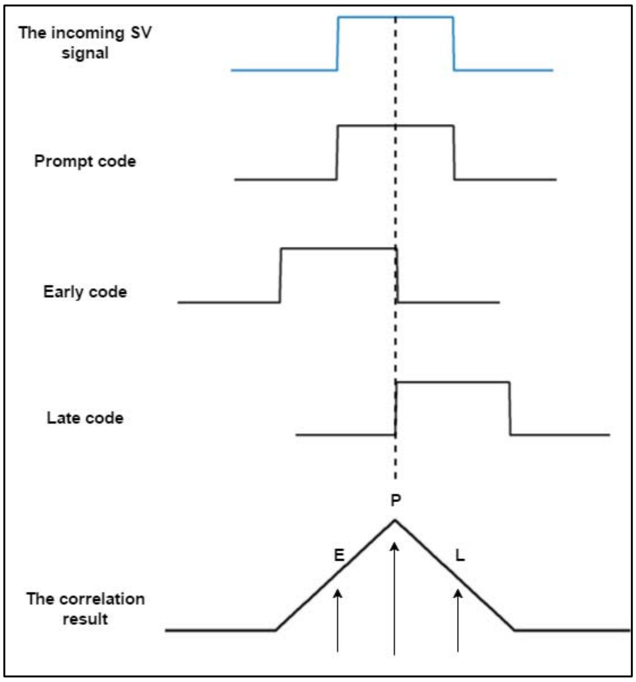


Fig. 9. Early, prompt, late correlation

are produced as two-phase delayed versions of Prompt (P) code [3]. To overcome above mentioned effects, the phases of six local codes (I_E, I_P, I_L and Q_E, Q_P, Q_L) are correlated simultaneously with the incoming signal. Finally after determined Doppler frequency shift and PRN code, navigation message is extracted from the signal. When this process is performed for four different satellites, the 3D position of the receiver on Earth can be found.

IV. Conclusion

The usage of satellite based positioning systems such as GPS, GLONASS, COMPASS and Galileo have been increasing in the worldwide and these systems are used for various civil applications such as road transportation, aviation, scientific researches, security etc. The code correlation operation in GPS receiver is the most important step for satellite signal acquisition. In this study, the code correlation technics used in GPS receivers are presented and the correlation process is simulated with an example in MATLAB environment.

In near future, it is planned to receive all satellite signals (GPS, Galileo, Glonass, Compass etc.) via only one receiver with the framework of interoperability and compatibility program. The most important difficulty in this development program is the usage of different modulation and signal processing technics such as BPSK (Binary Phase Shift Keying), QPSK (Quadrature Phase Shift Keying) and BOC (Binary Offset Carrier). Due to the new progress in satellite positioning systems, the existing modulation and correlation techniques used in the GNSS receivers may need to improve forthcoming years or find the new methods.

References

[1] E. D. Kaplan, and C. J. Hegarty, Understanding GPS Principles and Applications, 2rd ed., United State of America: Artech House, Inc., 2006, pp. 153-179

[2] J. W. Betz, Engineering Satellite-Based Navigation and Timing Global Navigation Satellite Systems, Signals, and Receivers, New Jersey, John Wiley & Sons. Inc., 2016, pp. 1-59

[3] J. Bao, Y. Tsui, Fundamentals of Global Positioning System Receivers: A Software Approach, 1rd ed., New York: John Wiley & Sons, Inc., 2000, pp. 73- 117

[4] G. Blewitt, “Basics of the GPS technique: observation equations”, in Geodetic Applications of GPS, Swedish Land Survey, pp. 9-15, 1997.

[5] NAVSTAR GPS, Global Positionin System Standard Positioning Signal Specifications, 2rd ed., June 2, 1995, pp. 14-34

[6] http://www.colorado.edu/geography/gcraft/notes/gps/gif/signals.gif (Accessed: 26- April- 2017)

[7] R. B. Langley, “Smaller and smaller: the evolution of the GPS receiver”, GPS World Magazine, Vol. 11, No.4, pp. 54-58, April 2000.

[8] M.S. Braasch, and A. J. V. Dierendonck, “GPS receiver architures and measurements”, in Proceedings. of The IEEE, vol. 87, no. 1, pp. 48-64, January 1999.

[9] http://www.navipedia.net/index.php/System_Design_Details#Applications_Processing (Accessed: 26- April- 2017)

[10] K. Borre, D. M. Akos, N. Bertelsen, P. Rinder, and S. H. Jensen, A Software-Defined GPS and Galileo Receiver: A Single-Frequency Approach, 1rd ed., Boston: Birkhuser, 2006, pp. 75-86

[11] J. G. Proakis, and D. G. Manolakis, Digital Signal Processing: Principles, Algorithms and Applications, 4rd ed., New Jersey: Prentice Hall, 2006, pp. 116-125

[12] A. V. Oppenheim and R. W. Schafer, Discrete-Time Signal Processing, Prentice -Hall Signal Processing Series, 3rd ed., Pearson, 2009, pp. 64-70

[13] R. E. Walpole and R. H. Myers, Probability and Statistics for Engineers and Scientists, 3rd ed., New York: MacMillan Publishing Company, 1985, pp. 432-438

[14] E. C. Ifeachor and B. W. Jervis, Digital Signal Processing: A Practical Approach, 2nd ed., Harlow, England: Prentice-Hall, 2002, pp. 243- 253