THE UNIVERSITY OF TURKISH AERONAUTICAL ASSOCIATION
INSTITUTE OF SCIENCE AND TECHNOLOGY

OPTIMAL FUSION OF MULTIPLE GNSS SIGNALS VIA KALMAN FILTERING AGAINST SPOOFING SOURCES

Master Thesis

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Sciences Institute Department

Electrical and Electronics Department

FEBRUARY 2016

THE UNIVERSITY OF TURKISH AERONAUTICAL ASSOCIATION
INSTITUTE OF SCIENCE AND TECHNOLOGY

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MASTER THESİS

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SELÇUK ŞAHİN, having student number 1303630008 and enrolled in the Master Program at the Department of Science and Technology at the University of Turkish Aeronautical Association, after meeting all of the required conditions contained in the related regulations, has successfully accomplished, in front of the jury, the presentation of the thesis prepared with the title of “Optimal Fusion Of Multiple GNSS Signals Via Kalman Filtering Against Spoofing Sources”

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I hereby declare that all the information in this study I presented as my Master’s Thesis, called “Optimal Fusion of Multiple GNSS Signals via Kalman Filtering against Spoofing Sources” has been presented in accordance with the academic rules and ethical conduct. I also declare and certify on my honor that I have fully cited and referenced all the sources I made use of in this present study.

03/02/2016
Selçuk ŞAHİN

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I would like, to say thanks to my supervisor Assist. Prof. Dr. Abedallatif BABA and Dr. Tolga SÖNMEZ for great patience, broad vision, sincerity and incredibly useful advice.

FEBRUARY 2016 Selçuk ŞAHİN

Dedicate to My daughter

FOREWORD

The aim of this thesis is to develop preventive methods against signal pollution attack and deception which can come from the environment.

Therefore, four different Global Navigation Satellite System (GNSS) signals are going to be used so as to verify this thesis.

The signals coming from these satellite systems will be envisaged inferentially and will be described with a linear model accordingly, the last formed linear model will be tackled with Kalman filtering method as it will be finally simulated using the Matlab™ program in this thesis. GPS, GALILEO, GLONASS, and COMPASS are the most famous global navigation satellite systems in our days. Some of them are mostly used around the world while the others are going to be activated in short time. All these systems will be cited in our thesis for sampling purposes.

This thesis is explaining the operation principles of four GNSSs in detail. Then, Kalman Filter Algorithm operational flow and principle are the topics which will be illustrated in the thesis.

Consequently, according to the data which will be obtained in the simulation step, filter performance will be calculated and the assessments will be done accordingly.

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LIST of ABBREVIATION

KF	Kalman Filter
EKF	External Kalman Filter
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GLONASS	Global Navigation Satellite System (Russian)
N/A	Not Applicable
SOL	Safety of Life
CDMA	Code Division Multiple Access
FDMA	Frequency Division Multiple Access
Q Phase	Quadrature Phase
NDS	Nuclear Detonation Signals
CS	Commercial Service
PRS	Plenary Regulation Service
SAR	Search and Rescue
EIRP	Equivalent Isotropic Radiated Power
LSM	Least Square Method

ABSTRACT

OPTIMAL FUSION OF MULTIPLE GNSS SIGNALS VIA KALMAN FILTERING AGAINST SPOOFING SOURCES

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Poor quality signal reception because of a noisy environment, spoofing signals that emerge under the name of asymmetric threat which is used in war strategies as a new war method make it difficult to take the desired knowledge from GNSS systems.
This situation causes some place and time deviations (errors) in the received data from any navigation systems.
Susceptance to such effects in navigation systems causes disruptions, deteriorations, and big accidents when using military and civil navigation systems.
In this thesis, we are trying to explain and prove that we can protect a multiple satellite system by using a Kalman filter implementation against deception spoofing and jamming signals which can come from the environment.

Keywords: Spoofing signals, Asymmetric threat, jamming signal in navigation systems.

ÖZET

ALDATMA KAYNAKLARINA KARŞI KALMAN FİLİTRE KULLANARAK ÇOKLU GNSS SİNYALLERİNİN OPTİMUM BİRLEŞTİRİLMESİ

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Şubat 2016, 69 Sayfa

Günümüzde, gerek ortamdaki gürültüden dolayı kalitesiz sinyal alımı, gerekse asimetrik tehdit adı altında ortaya çıkan ve yeni bir savaş metodu olarak savaş stratejilerinde yerini alan, aldatma sinyalleri veya karıştırma yöntemi, GNSS sistemlerinde istediğimiz bilgileri alabilmemizi zorlaştırmaktadır.

Bu durum navigasyon sistemlerinde yer ve zaman sapmalarına sebep olmaktadır.

Bu şekilde navigasyon sistemlerindeki sinyal bozukluğu, hem askeri sistemlerin, hem de sivil amaçlı navigasyon sistemlerinin kullanımlarında aksamalara, bozulmalara ve bazen de büyük kazalara sebebiyet vermektedir.

Bu tezde açıklamaya veya ispatlamaya çalışılan, dışardan gelebilecek aldatma veya karıştırma sinyallerine karşı, Kalman filitre uygulaması kullanılarak, çoklu uydu sistemlerine koruma sağlanmasıdır.

Keywords: aldatma sinyalleri, asimetrik tehdit, karıştırma sinyali, navigasyon sistemlerindeki.

INTRODUCTION

The use of advanced technical approaches and filtering methods to treat noisy signals represents a modern way that both academicians and scientists apply in their studying for many years.

Kalman filter is the base of any filtering method that depends on gaussian probabilistic distribution in any state space. This method that has a high predictability is one of the most successful approaches which are in use in several areas of our life.

The aim of this project is to detect an external attack such as a spoofing signal which affects the satellite navigation systems and filters out the spoofing signal by rejection in the fusion process. For many years, the function of GNSS has been worked as faultless and flawless. Formerly, jamming and spoofing became a concern for the military. Jamming is intentional interference targeting the unavailability of the system and spoofing is transmitting a false position/time towards a target GNSS receiver. But recent events started to change this situation. For example: the unintended jamming of Newark Airport, by an UPS driver with a 100 US$ device available on eBay; the capturing of a US drone using a GPS spoofer by Iran; the demonstration of students from the University of Austin, Texas, US, to hijack a 80 million dollar Yacht with a self-made spoofer as well as their laboratory demonstration to use this spoofer to tamper the phase measurement units used for energy network synchronization and control [30].

In [31] they propose a detection and protection scheme consisting of several statistical tests, based on the computations of moving variances of Doppler offset and SNR estimates, together with a consistency test of the PVT (position, velocity, time) computation. They evaluate the performance of the proposed scheme through simulations and using a measurement setup consisting of a Spirent GSS8000 full constellation simulator whose output is combined with the one from a rooftop GPS antenna before being fed to a receiver front-end.

In general, the spoofers have a major limitation. They must have several correlated GNSS signal in order to transmit and present a truthful navigation solution to the receiver. But different GNSS signals coming from a single transmitter have essentially the same spatial tag which can be utilized to discriminate the spoofing signals In [32] they use an antenna array to nullify the signals that are coming from a jammer or spoofer source. This method requires highly specialized antenna array and embedded processing.

[33] focuses on a robust and precise car navigation system, which can also be used in GNSS-denied or spoofed scenarios. The system is based and designed for so called `On Board Units' (OBU), which are already used for professional road toll and tracking applications. The system combines GNSS and dead reckoning (DR) trajectories, based on odometry and inertial navigation. Using other sensors also help to detect the spoofing signal presence.

In this thesis, four Global Navigation Satellite Systems are used to simulate these attacks. These systems are GPS, Galileo, GLONASS, and Compass.

The signals processed by these systems will be modeled with Kalman Filter method and will be simulated with the help of Matlab™. Fınally, three different scenarios wıll be provided to prove the proficiency of our approach by showing that stopping a spoofing signal coming from outside will be determined by the system.

CHAPTER ONE

GLOBAL NAVIGATION SATELLITE SYSTEMS (GNSS)

1.1 Global Navigation Satellite Systems (GNSS)

Humankind's have observed to the heavens with the great eagerness to find extraordinary signs since the beginning of history. Some of these people succeed in deciphering the secret of stars and space. And throughout the history, lots of studies and developments were realized in science. For example, first Egyptians used to rebuild the destroyed places by river flood. Then, Greeks and Romans used to distance control points to determine the settlement fields. Later Snell van Royen made the first angle measurements between far distance regions in order to determine coordinates. Accordingly, triangulation calculation was realized on larger fields by French Picard and Cassini [1]. The counts of these explorations have increased further with the rapid development of technology from the past to today. Now, developing the satellite systems is so important topic to ease people life from navigation to communication.

Some examples of current Global Navigation Satellite Systems (GNSS) applications;

Personal Navigation: These applications are helping people to navigate on feet or cars. This is currently used with cell phones and PDAs.

Aviation applications: This includes route navigation as well as the certainty approach and landing.

Automotive applications: GNSS have contributed the development of automobile sector. It represents a very important used system by drivers to get a destination from departure point in minimum time.

Weak signal navigations: This system is generally used in indoor environment applications. GNSS solutions must be optimized for a strong signal.

Marine applications: This is one of the civil applications for GPS because it is really suitable for this use. GPS is standard equipment for all type of boats.

Space applications: They have been basically used in low Earth orbit satellites and also used in space vehicles operating. GPS has a high potential to be used in these applications.

Agriculture, forestry and resources exploration: GNSS is used for geological monitoring, forest management, and oil explorations.

Military applications: As an example, military missions and missile defense systems. To achieve navigation purposes in enemy territories.

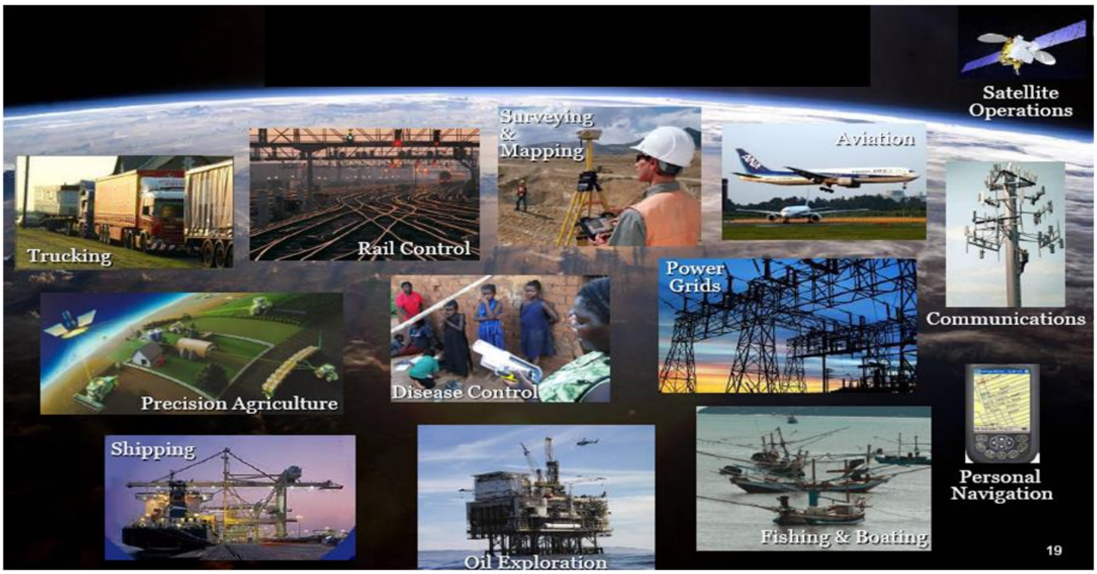


Figure 1.1: Examples of GNSS Applications

Global Navigation Satellite System (GNSS) generally has been defined as time and position detection system that includes a set of satellites for triangulation. Four GNSS are known in our days, the most prevalent systems are the American Global Positioning System (GPS) and the Russian Global Navigation Satellite System

(GLONASS). While the others infrequently used systems are the Chinese (COMPASS) and the European (GALILEO) [2].

1.1 Global Position System (GPS)

GPS enables users to obtain information such as location, speed, and time at any place and time on Earth and in all weather conditions by using the satellites signals. At the present time, it is used in many sectors that are military, commercial and civilian. And there are nearly 20 million users worldwide [3].

In 1973 to cope with the constraints of old navigations systems the USA started the GPS Project. The project was based upon the mutual working of 24 satellites which spin around the world. The first satellites were launched in 1978. The first 10 satellites that were based on development are called “Block I”. Then between 1989 and 1997 the launched 28 satellites are named as “Block II”. Also, the improved final 19 satellites are known “Block IIA”. And in 1997, the first third-generation GPS satellite, named “Block IIR”, was launched for taking places of other satellites. After these stages, currently, there are 31 satellites served of GPS [4].

The GPS satellites move around to the Earth at an altitude of about 20,000 km with 3.9 km/sec speed. The GPS satellites are not in a geostationary orbit, however, they can spins around the world two times per day. Each satellite transmits radio waves towards Earth to contain information of position and time. Then we can take this information by using GPS receivers, which can detect and decode this information [5]. The signal broadcasted by a satellite includes the location knowledge of satellite and transmission time knowledge of broadcasted signal. But GPS receiver needs position knowledge from at least 4 satellites in order to calculate its own location. This requirement is a necessity not only in GPS system but also in all other GNSS systems.

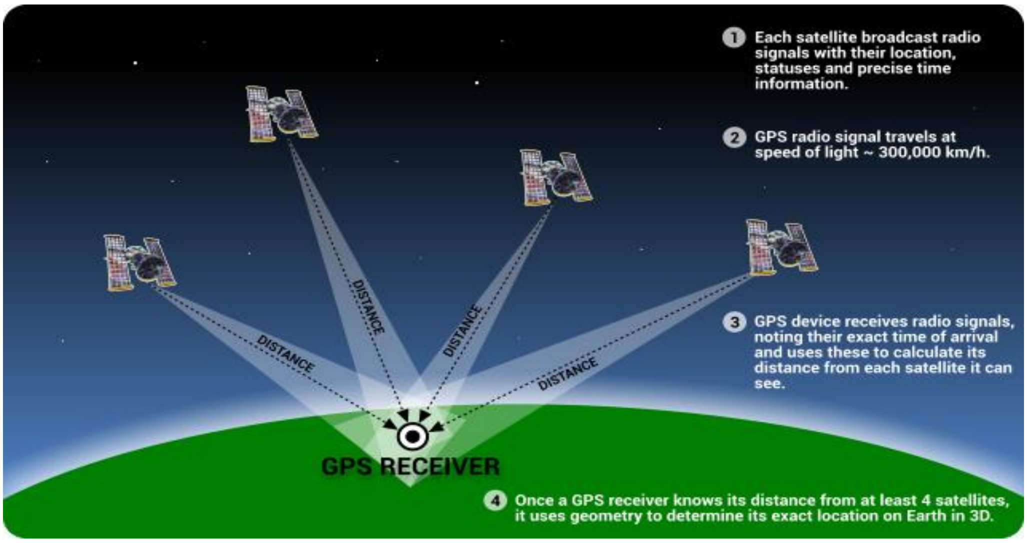


Figure 1.2: GPS System Working Principle [9]

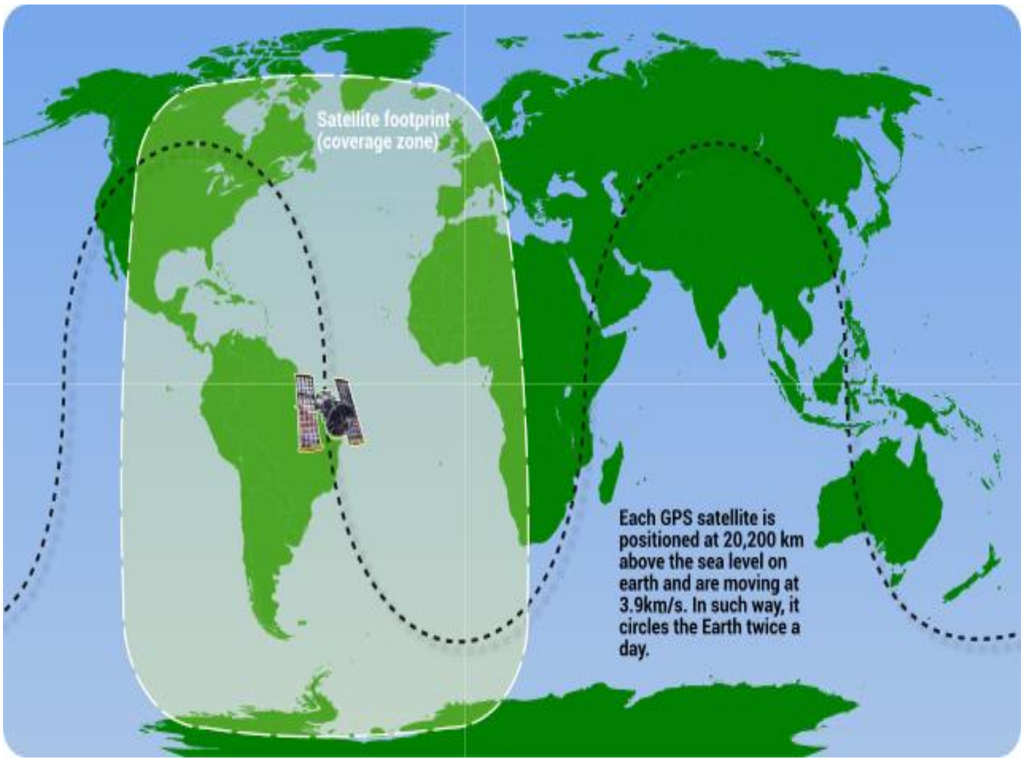


Figure 1.3: GPS Satellite Path [9]

GPS system can be used by everybody who has a GPS receiver. While GPS, Galileo, and Compass systems work with CDMA (Code Division Multiple Access), Glonass system works with FDMA (Frequency Division Multiple Access).

Well, what is CDMA? CDMA (Code Division Multiple Access) is a transmission technology which uses spread-spectrum technology.

CDMA technology enables users to speak different languages. In other words, CDMA technology forms a distinct channel by giving the different code to different users which resemble people communicating with different languages.

The whole satellite signals have been produced from 10.23 MHz which is the basic frequency. As for basic frequency which is manufactured from atomic clocks. When the basic frequency is multiplied by 154, we get L1=1575.42 MHz which is L1 carrier wave frequency and when it is multiplied by 120, we get L2=1227.60 MHz which is L2 carrier wave frequency.

P-code is 10.23 MHz which is a basic frequency. C\A code is 1\10 of the basic frequency. In short, it is 1.023 MHz L1 carrier wavelength is 19.05cm, L2 carrier wavelength is 24.45cm, the wavelength of P-code is 29.31 meter, and the wavelength of C\A code is 293.1 meter. L1 signal has been modulated with both P-code and C\A code. L2 signal has been modulated with only P-code. L1 and L2 signals have been modulated continually with navigation bits.

GPS data stream are provided from satellites to user by electromagnetic waves. Each GPS satellite has 2 basic frequencies to transmit location. These are L1 and L2.

Data flow between satellites and control section is made from S-band and data flow between users with satellites is made from L-band.

C\A code is used for modulation in only L1. Its period is very short. The reason for this selection is to provide the lock of GPS receivers to satellites. P-code is used for modulation in both of L1 and L2 carriers. P-code has a period of 1 week.

The knowledge of frequencies used actively at GPS system is as below;

- L1: 1575.42 MHz (C/A and P/Y code, L1C)
- L2: 1227.60 MHz (L2C and P/Y code)
- L3: 1381.05 MHz

– L4 1379.913 MHz
– L5: 1176.45 MHz

The usage goal and phase array of the written frequency are shown in Table 1.1.

Band	Frequency (MHz)	Phase	Original Use	Modern Use
L1	1575.42 10.23×154	In-phase (I)	Encrypted Accuracy code P(Y)	
		Quadrature-phase (Q)	C/A, L1 Civil (L1C) and Military (M) code	Coarse-acquisition code (C/A)
L2	1227.60 10.23×120	In-phase (I)	Encrypted Accuracy code P(Y) code	
		Quadrature - phase (Q)	Non-modulated Carrier	L2, Civil (L2C) code and Military (M) code
L3	1381.05 10.23×135		For Nuclear Explosion (NUDET) The payload for Detection Array (NDS); nuclear detonation signals/high energy infrared events. Using for implement Nuclear test ban treaties.	
L4	1379.913 10.23×1214/9		(No Transmission)	For additionally studied ionosphere correction

L5	1176.45 10.23×115	In-phase (I)	(No Transmission)	Safety-of-Life (SoL) data signal
		Quadrature-phase (Q)		Safety-of-Life (SoL) Pilot signal

Table 1.1: GPS Frequency Table [6]

The current GPS systems consist of 3 segments.

1. **Satellite Segment (Space Segment):** This segment consists of minimum 24 satellites (18 actives, 6 back-ups) and it is the center of the system, like its heart. The satellites are located in orbit 20,000 km above the earth's surface that is named "High Trajectory". They have great wide areas of vision thanks to this great altitude. It transmits the navigation signals so that users can calculate their locations. In order to calculate the location, it is necessary that a receiver locks in at least. Around high buildings, hilly and rough regions or crowded places, the GPS signal declines.

The satellites can take a tour around the world in 12 hours. And they work with solar energy and are designed to be used at least ten years. Also, they have backup batteries group against energy interrupts and have small rocket igniter to adjust orbit corrections.

2. **User Segment:** This segment is formed by civil and military users. It includes GPS receivers which convert the signal into space into position, velocity and time estimates. The power of the signal is less than the one quadrillion of the power consumed in a lamp. Four satellites are needed to calculate the four dimensions of X, Y, Z (position) and time. Also, GPS receivers can be used for navigation, time distribution, and other applications. The number of available receivers is not limited because they act as passive manner.

3. **Control Segment:** It provides to work actively. The control system is essential to update satellites and control the satellites so that they remain at determined orbits.

It consists of a tracking system. And the monitor stations take signals from the space vehicles and measure the signal. The space vehicles are located into orbital models for each satellite. The models calculate orbital data and clock corrections. The control station uploads orbital and clock data to space vehicles and then the satellites send them to GPS receivers. There are five control situations in the world: Hawaii, Kwajalein, Colorado Springs (Main center), Ascension Island and Diego Garcia). The four of them are unmanned, and the one is the main center that is manned. The unmanned centers send the collected information to the main center. The main center evaluates and regulates this information and report to the satellites. [6-11]

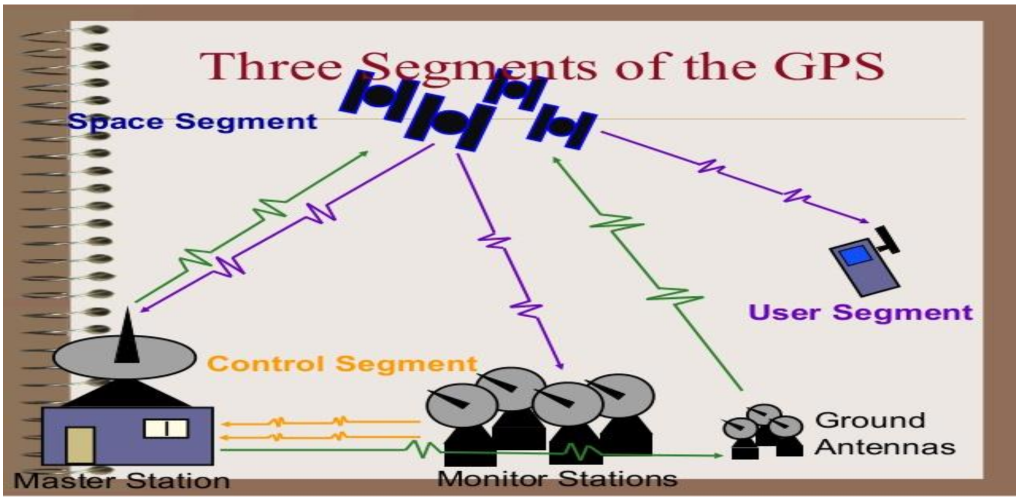


Figure 1.4: Three Segments of the GPS

1.2 Galileo (European Global Navigation Satellite System)

The opening of GPS system to the usage of civil users by 1983 plane accident glittered as a revaluation. The usage of GPS and GLONASS systems for military purposes made the European Union to set up a new navigation system.

GALILEO system was started to serve civilian usages in the European Union countries under the leadership of Germany with the contribution of France, England, and Italy. Firstly, GALILEO navigation system was started formally by European Space Agency on 26 May 2003 with 4 different designs.

Especially navigation in land, sea and air vehicles to achieve search and rescue missions were focused. GIOVE-B, the second satellite on 27 April 2008 was launched. The system planned as 27 in service and 3 extras, totaling 30 satellites actively by the end of 2015.

The working principle of GALILEO system is same with GPS system. But the signal frequency is different. Accordingly, GALILEO system has the structure which works at different frequency interval with different usage purposes. These signals are;

1164-1215 MHz (E5a and E5b),
1215-1300 MHz (E6) and
1559-1592 MHz (E2-L1-E1)

Accordingly,

- 6 signals over E5a, E5b and L1 frequencies for Open Service (OS) and Life Security Services (SOL) users
- 2 signals on E6 carrier frequency with encoded length detection for Commercial Service(CS) users
- the detection code of encoded lengths of 10 signals and have been given the usage of Plenary Regulation Service (PRS) users, at last, two which include data E6 band and the other L1 band.

According to other GNSS system, Search and Rescue (SAR) function which is a different service of GALILEO works based on the CORPAS-SARSAT system. Every GALILEO satellite carries a transmitter which detects immediate aid calls.

This specialty usage is superiority with respect to other systems. Also, GALILEO system leans on CDMA (Code Division Multiple Access) principles like GPS system [10, 12]

1.3 GLONASS (Globalnaya navigatsionnaya sputnikovaya sistema)

GLONASS system is a second GNSS system which was started to improve GPS system by the Soviet Union in 1976.

The system was started to develop in 1967 and it has been in service in 1995.

But with the collapse of The Soviet Union, Glonass didn't show any activity during the next 6 years. Vladimir Putin reactivated the program in 2001 and with the launch of new satellites the systems covers nearly the whole world with 24 satellites.

Although the system has worked similarly with GPS, GALILEO and COMPASS as a task, the working system has been regulated by FDMA (Frequency Division Multiple Access), not CDMA (Code Division Multiple Access).

Basically, All satellites convey the same code as the own standard sensitiveness signal. But FDMA (Frequency Division Multiple Access) which has 15-channel and division frequency multiple access and known between 1602.5625 MHz with 1615.5 MHz as an L1 band each one is conveyed at a different frequency. In order to calculate the exact central frequency, Equation is 1602 MHz + n + 0.5625 MHz; this n is a place that is (n=0, 1, 2, 3…..24) of the frequency channel number of a satellite. Signals among 25-27 dBW (316-500 Watt) are conveyed in a cone of 38^0 at an EIRP (Equivalent Isotropic Radiated Power) as are used the right-hand circular polarization.

In GLONASS GNSS, there are 24 usable satellites. These satellites use FDMA working system. For using FDMA, each satellite takes one number and calculates frequency that makes communication by using the last equation. However, over the world each satellite has a pair of satellites that is on antipole side. Thus, in the system, up to 15 satellites can be used.

But the FDMA working system, with the aim of transforming the CDMA working structure which is used with other GNSS systems, has continued the workings since 2008.

Frequency interval is not stable like other GNSS systems. For this reason, it works between obvious frequency intervals. [10, 12]

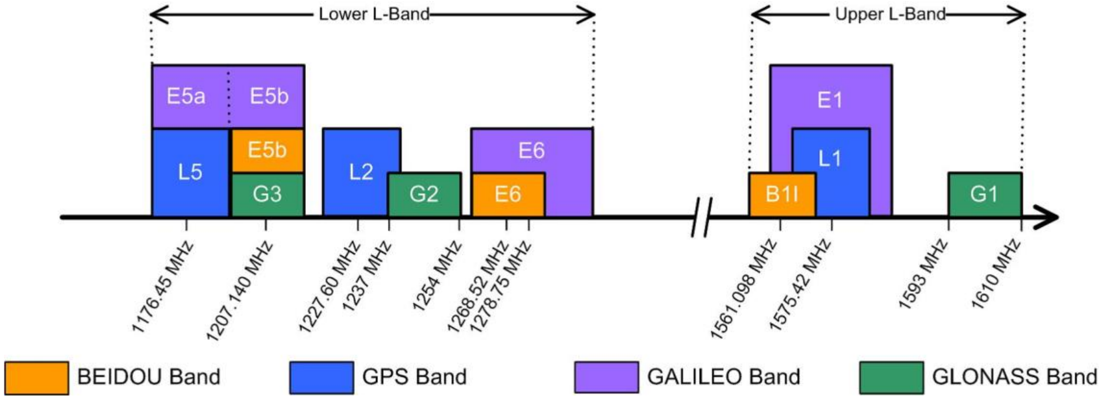


Figure 1.5: Table of GNSS Frequency [10]

1.4 Compass (BeiDou-2)

Beidou-2 GNSS system is going to start offering its service for a limited number of users by coming into operation in 2020.GNSS system called as Beidou-1 consists of two different satellite groups like a test system and full-scale navigation system.

The system called as Beidou-2 and used for the experiment formally consists of 3 satellites.

But Beidou-2 GNSS system, called as COMPASS and becoming the second belt of the system is going to be gone into action as GNSS system which consists of 35 satellites. Forthcomingly, 10 satellites went into action in December 2011 in China. 2020 has been envisaged date for commissioning the entire system.

COMPASS system is using the CDMA working principles like the GPS and GALILEO systems. It has been given the working frequency of the system in Figure 1.3.

China attended GALILEO system in 2003 and was started common working. Accordingly, E1, E2, E5B and E6 frequencies were assigned to COMPASS system with the aim of common usage.

In current situations, the coverage zone of COMPASS (Beidou-2) GNSS system has been showed in Figure 1.4. [10, 12, 13]

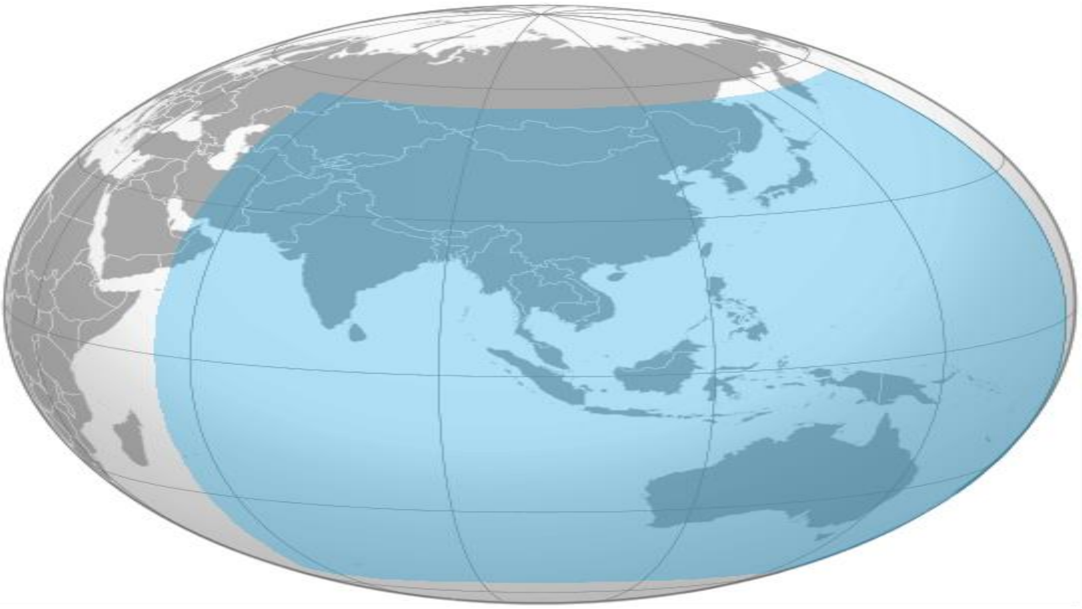


Figure 1.6: COMPASS (Beidou-2) Coverage Zone [13]

1.4 What are the Advantages and Disadvantages of the CDMA Technique?

1.4.1 The advantages:

- Efficient practical utilization of fixed frequency spectrum.
- Flexible allocation of resources.
- Many users of CDMA use the same frequency, TDD or FDD may be used

- Multipath fading may be substantially reduced because of large signal bandwidth
- No absolute limit on the number of users, Easy addition of more users.
- Impossible for hackers to decipher the code sent
- Better signal quality
- No sense of handoff when changing cells
- The CDMA channel is nominally 1.23 MHz wide.
- CDMA networks use a scheme called soft handoff, which minimizes signal breakup as a handset passes from one cell to another.
- CDMA is compatible with other cellular technologies; this allows for nationwide roaming.
- The combination of digital and spread-spectrum modes supports several times as many signals per unit bandwidth as analog modes.

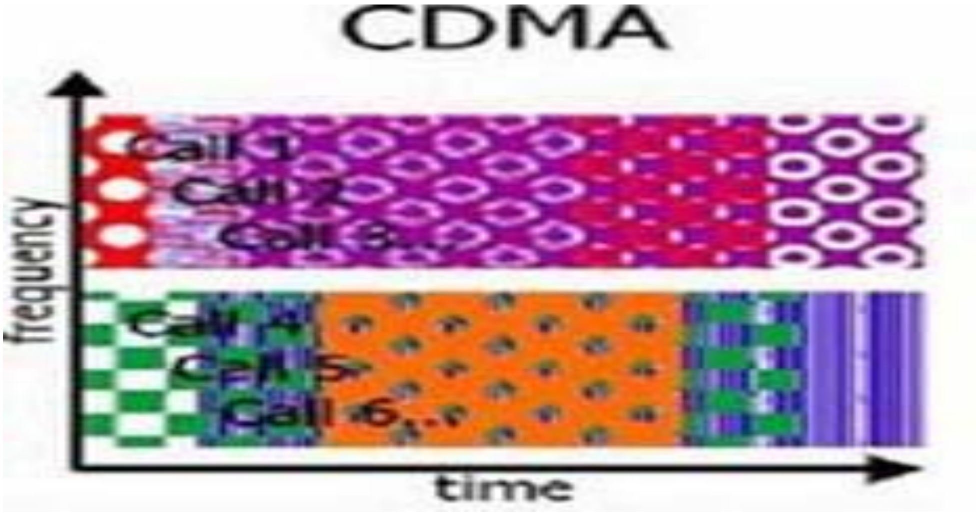


Figure 1.7: CDMA (Code Division Multiple Access)[16]

1.4.2 The Disadvantages:

- As the number of users increases, the overall quality of service decreases
- Self-jamming

- Near- Far- problem arises [10, 14, 15]

1.5 What are Advantages and Disadvantages of the FDMA Technique?

1.5.1 The advantages:

- FDMA technique doesn't need any base control station.
- Data that transferred between each station to another during the transmission process will not be lost.
- After the transmission of data, the effect on the delay distortion will be so small and it can be ignored.
- There is no need for network timing.
- The channel operations in FDMA are simple.
- In FDMA, the reduction of the information bit rate has a good effect on the capacity.

No need for any equalization.

- Because of the transmission is continuous, there is almost no need for bits that are responsible for synchronization.
- Simplicity in FDMA algorithms. [10-16]

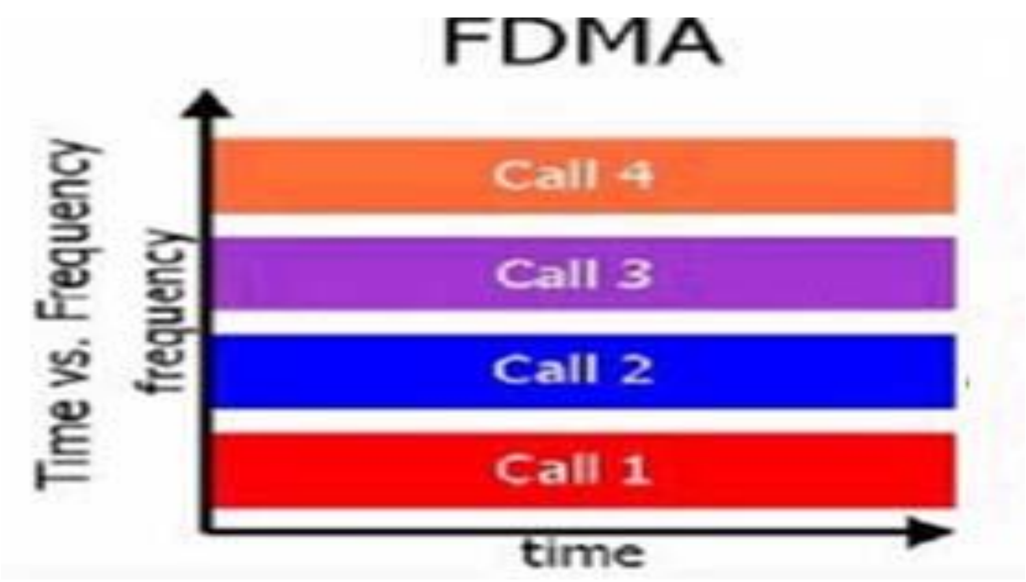


Figure 1.8: FDMA (Frequency Division Multiple Access)[14]

1.5.2 The Disadvantages:

- In the FDMA technique, it is impossible for the stations to receive data from more than one transmission source.
- One of most important thing in communication systems is the maximum data rate which is small and fixed for every channel in FDMA.
- Because of the guard bands, the capacity of the FDMA will be decreased.
- Increasing the cost of FDMA, since the band filters are narrow that can't be recognized by VLSI.
- FDMA requires special filters to avoid any interference between the narrow channels[10,14,16]

SECOND CHAPTER

KALMAN FILTER

2.1 What is the Kalman Filter?

Kalman Filter was found in the 1950s by Rudolf Emil Kalman who was a mathematical system theorist. But, it caused a revolution in estimation such that it is used at Apollo Space Vehicle by NASA in the 1960s.

Kalman Filter is a prediction algorithm, working with the minimization of the occurring error while it predicts iteratively the current state. Based on a system model, the process tries to catch the real value constantly. As calculating with Kalman Filter, if the values of stochastic noise and the direction of random noise take into account, the estimated values can be very well.

According to the traditional estimator, Kalman Filter is a very strong filter from the point of predicting the situations of the system which cannot be measured. Kalman Filter admitted as the most important prediction algorithm is used from aircraft to mobile phones, from robotic systems to stabilization systems [17-19, 20].

2.2 How does Kalman Filter Work?

Kalman Filter Algorithm solves errors with Least Square Method (LSM) by working recursively in real-time on noisy data. It reveals the mathematical optimization of the next state generated by modeling the physical characteristics of the actual system.

In this case, the idea is to compare with the model estimate and the observation estimate. Thus, Kalman Gain determines the difference between both estimates. A large gain indicates a rapid response of the input measurement in updating the state while a small gain yields a slower response to that measurement. For this reason, the Kalman gain value forms a conclusion.

The method used here works to produce closer predictions to real unknown values from the prediction which can be obtained based on model estimates.

Every measurement which is done by calculating the situation variance which depends on time is derived at some uncertainness with known values continues until this estimate from the low uncertainness. Figure 1.5 shows the prediction loop of Kalman filter.

The following points shouldn’t be forgotten before Kalman filter method is dare modeling;

- Although Kalman filter is called a filter, it is an estimator mostly.
- It cannot be completely dominated to Kalman filter. It can be brought to the desired level by playing only values
- Kalman filter is an iterative method. Namely, the output of the previous step provides input for modeling as the input of the next value. This situation continues until declined uncertainties [18-21]

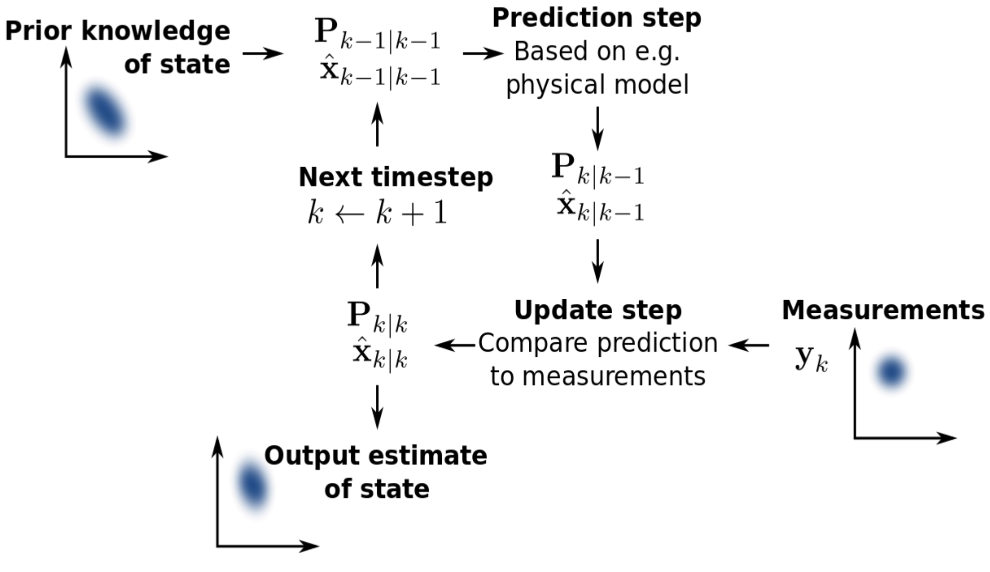


Figure 2.1: Kalman Filter Estimate Method [19]

2.3 Kalman Filter Formulas

There are many formulas which are difficult for being understood to achieve Kalman filter calculations. But, these formulas happen to be reached the following formula when the state matrices are thrown

$$x_k = k_k . z_k + (I - k_k) . x_{k-1} \tag{2.1}$$

x_k = State Value

z_k = Measurement Value

k_k = Kalman Gain

x_{k-1} = Previous State

I = Identity Matrix

Accordingly, ‘’*k*’’ symbol which has been indicated as a subscript in the above formulas indicates current state or phases. Namely, if the sampling period is taken 1 ms and k symbol is given 1 value, discrete time intervals are accepted as 1 ms.

x_k , is the value in the state variety of *k* series and is tried to be found the estimate in the (*k*) series.

z_k , is the measurement value. x_k , is estimated by using this measurement.

Finally x_{k-1} is estimating the value of the current signal in the previous state.

k_k , is Kalman gain which is the most important element in the last equation and its value has to be calculated according to each case in order to find the best estimate value [20].

2.4 Creating a Model with Kalman Filter Method

One of the most important conditions which are necessary to be satisfied prior to creating a model with Kalman filter to match Kalman filtering condition to a problem which we intend to solve

Thus, It should be stated the creating model with Kalman filter by writing the formulas which will be used.

$$x_k = A x_{k-1} + B\mathrm{u}_k + w_{k-1} \tag{2.2}$$

$$\mathrm{z}_k = H x_k + v_k \tag{2.3}$$

A= Dynamic coefficient matrix

x_k = State Value

x_{k-1} = Previous State Value

B = Coupling Matrix

u_k = Control Input

w_{k-1}= Previous Process Noise

H= Measurement Sensitivity

v_k = Measurement Noise

z_k = Measurement Value

In this chapter, the model is formed by using the formula cited in the last equations 2.2 and 2.3.

A, B and H elements are the general representation. These elements are calculated as a constant number at many signal problems.

- w_{k-1} Represents the previous process noise, v_k represents measurement noise.
- u_k is a control signal, in most studied cases, there's no control signal u.
- x_{k-1} Is given as the previous value of x_k and changes as long as the process continues.
- z_k, we may think to use a device in order to determine the measurement which may be noisy.

The noisy elements in both equations are tackled as the first-degree equation, in other words, it is tackled as Gaussian probabilistic distribution. But any signal in the real world must not be considered and treated as a Gaussian. It can be acknowledged that exists only with an approximation. The true estimate which will be obtained in this way provides real results, even if the parameter values are badly estimated.

After having the suitable model, the determination of the beginning values of parameters will be required.

There are two phases to be applied in this model:

- Prediction Time Update
- Correction Measurement Update

Both phases given above have been used for the (*k*) state of equation 2.2 and equation 2.3 and have been showed in Table 1.

(Prediction/Time Update)	**(Correction/Measurement Update)**
1. Previous Estimate $\hat{x}_k^- = A\hat{x}_{k-1} + w_{k-1}$ 2. Previous Covariance Error $p_k^- = Ap_{k-1}A^T + Q$	1. Kalman Gain $k_k = p_k^- H^T (Hp^-_k H^T + R)^{-1}$ 2. z_k Prediction of Measurement Location $\hat{x}_k = \hat{x}_k^- + k_k (z_k - H\hat{x}_k^-)$ 3. Updating of Error Covariance $p_k = (I - k_k H) p_k^-$

Table 2.1: Estimate/Time-Regulation/Measurement Update

As we have indicated in advance, *A*, *B* and *H* elements are largely the constant matrix and these elements take *I* value at much modeling or problem. *R* (Measurement Noise Covariance) and *Q* (Process Noise Covariance) elements illustrated in Table 2.1 represent the measurements and the process noise statistics respectively.

The process cited above forms the input of the next estimate of the state. And this will be the case for each iteration. Accordingly, x_{k-1} is the previous estimate value. p_k^- is covariance of the previous error. These two values are described and used as the first input in update/regulation levels for the next measurements. Namely, these two values become the input for the next process. They are a matter to calculate the real x_k value at the last of processes in Regulation/Measurement Update chapter.

The value which has been obtained is the value in "*k*" time of *x* which is the desired result.

The second value in this calculation is p_k which represents the error covariance value. These two values at the moment (*k*+1) are indispensable for the rest of this process. When the achieved calculations are analyzed, the obtained results or every value was given guessingly to approach the real value will be found.

Consequently the calculations which are done from the estimated previous states, will be used to determine the error covariance and the base error covariance (p_k), the base measurement value (z $_k$) the estimate measurement value ($\hat{x}_k$) and Kalman gain (k_k). The values which are determined here become inputs for the next iteration. The loop which is formed guarantees in most cases getting the best convergence toward the real state. Our estimate presented here gets better for each new iteration of the last explained loop which is normally called Estimate / Time-Regulation / Measurement Update [18, 19, 22, and 23].

2.5 The Extended Kalman Filter

The extended Kalman filter (EKF) provides approximately the maximum forecast of probability for nonlinear systems. The average and covariance are updated iteratively. Also, it must be derived to estimate random variable in the first-degree linearization of dynamics. Thus, the nonlinear dynamics are approximated by this derivative towards the time varying linear dynamics [24].

The nonlinear state-space model for using EFK is written as shown in (2.4) and (2.5).

$$x_{k+1}=f(k,x_k) + w_k \tag{2.4}$$

$$y_k=h(k,x_k) + v_k \tag{2.5}$$

w_k and v_k are the process and measurement noises respectively, they are supposed zero-mean white Gaussian. R_k and Q_k are the covariance matrix. $f(k,x_k)$ is the transition matrix of nonlinear systems while $h(k, x_k)$ is the nonlinear measurement matrix. The simple logic in EKF is realized with providing return the real linear environment by derivation the transition matrix and measurement matrix. This is realized in two steps:

Step 1: To derive transition matrix and measurement matrix according to the model,

$$F_{k+1,k} = \frac{\partial f(k,x)}{\partial x} \ |x = \acute{x}_k \tag{2.6}$$

$$H_k = \frac{\partial h(k,x_k)}{\partial x} \ |x = \acute{x}_{\bar{k}} \tag{2.7}$$

Step 2: Firstly, the state and process matrix, F_{k+1} and H_k are calculated. This is made depending on the first degree Taylor Series. The state and process matrix are approximated to (2.6) and (2.7). Then the nonlinear state-space model is created by using these equations [25-26].

$$F\ (k,x_k) \approx\ F\ (x,\acute{x}_k) +\ F_{k+1,k}(x,\acute{x}_k) \tag{2.8}$$

$$H\ (k,x_k) \approx\ H(x,\acute{x}_k) +\ H_{k+1,k}(x,\acute{x}_k) \tag{2.9}$$

The summary of EKF equations is shown in Table 2.2.

The state-space model,

$x_{k+1}=f(k,x_k) + w_k$

$y_k=h(k,x_k) + v_k$

$$\mathrm{H_k} = \frac{\partial h(k, x_k)}{\partial x} \ |x = \acute{x}_{\bar{k}}$$

For k=0,

$\hat{x}_0 = E[x_0],$

$P_0 = E\left[(x_{0-}E[x_0])(x_{0-} E[x_0])^T\right],$

For k=1…

The state production,

$\hat{x}_{\bar{k}} = f(k, \hat{x}_{k-1})$

The fault covariance production,

$P_{\bar{k}} = F_{k,k-1} P_{k-1} F^T_{k,k-1} + Q_{k-1}$

The Kalman gain,

$G_k = P_{\bar{k}} H^T_k \, [H_k P_{\bar{k}} H^T_k + R_k]^{-1}$

The state updating,

$\hat{x}_k = \hat{x}_{\bar{k}} + G_k y_k - h(k, \hat{x}_{\bar{k}})$

The fault covariance updating,

$P_k = (I - G_k H_k) P_{\bar{k}}$

Table 2.2: The summary of EKF equations

THIRD CHAPTER

MULTI GNSS ALGORITHM AND MATLAB™ APPLICATIONS

3.1 Benefits of the Using Multi-GNSS

As it is well known, at the beginning GPS was the foremost positioning system, but currently, other satellite navigation systems such as GLONASS, Galileo, and Compass are used in the operation and are improved. GPS and GNSS are accelerating towards multi-frequency GNSS world. Like GPS, GLONASS system is continually developing. Also, the other systems as Galileo or Compass are getting closer to reality. A Multi-GNSS receiver is able to calculate position, velocity, and time by receiving the satellite signals broadcasted from multiple navigation satellite systems. Today, the CDMA is used for navigation in GPS receivers. But, interoperability and compatibility have been important issues for the design of Galileo, Compass and the regeneration of GLONASS system. If interoperable and compatible signals can be synergistically used in navigation systems, it would be beneficial to use this additional information. Consequently, we are making this study to illustrate the benefits of such a Multi-GNSS receiver in an interference environment. We will concentrate on civil signals in our analyzes. GPS is beginning to introduce three new civil signals L1C, L2C, and L5. And the GALILEO signals on E1, E6 and E5 will be open signals. COMPASS will have only two open signals which are similar to the GALILEO system. Similarly, GLONASS introduces also two new CDMA signals on L1 and L5. We will make some scenarios; simulate and compare the results of analyzes for Multi-GNSS receivers. [27-29]

3.2 The Modeling Multi-GNSS with Kalman Filter

In the second chapter, the Kalman filter was defined, discussed and explained; especially how to make the modeling with it. In this chapter, the modeling which is wanted to be used in the actual structure will be done for four GNSS systems. Then the created model will be simulated using Matlab™.

In our study, four GNSS systems have been used, but we can generalize to say more than four GNSS systems can be also used successfully, may be in the future. As we explained at the beginning of the thesis, what are we trying to do here is to keep out the signals of deception, noise or mixing apart from the system to guarantee that it is not included in the calculation. Thus, as illustrated in Figure 3.1, we will obtain a filtered output signal while the four GNSS channels are running in the model.

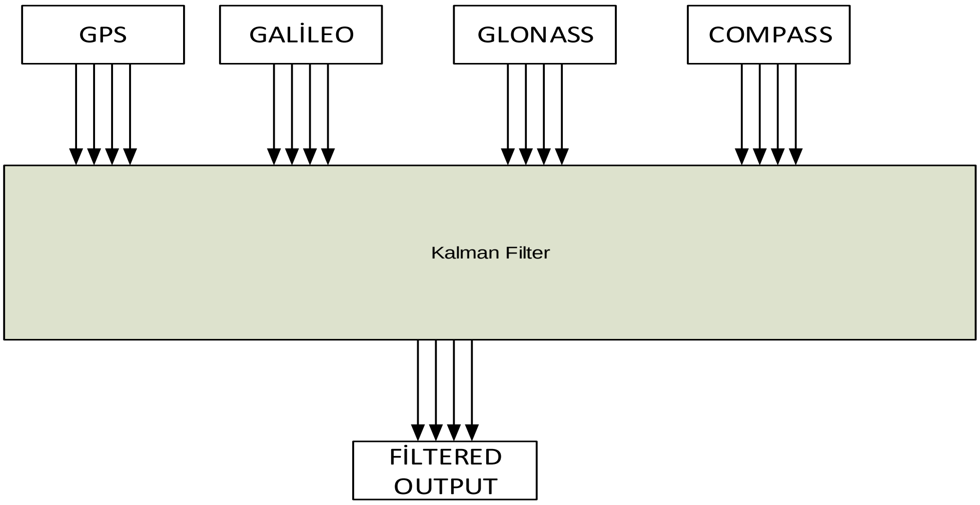


Figure 3.1 The analyzing of Multi-GNSS with Kalman Filter

However, the created system is linear and the value of each given input makes a suitable output. Some impacts that may come from the out of the system or some measurement errors of the model can affect its output.

The most important of these impacts is the system noises. In the created model two types of noises must be considered. These are Q (the process noise) and R (the measurement noise).

At First, the equations used in modeling should be noted;

$$x_k = \mathrm{A}\, x_{k-1} + \mathrm{Bu}_k + w_{k-1} \tag{3.1}$$

$$\mathrm{z}_k = \mathrm{H}\, x_k + v_k \tag{3.2}$$

$$x_k = \mathrm{A}\, x_{k-1} + \mathrm{Bu}_k + w_{k-1} => x_k = x_{k-1} + w_{k-1} \tag{3.3}$$

$$\mathrm{z}_k = \mathrm{H}\, x_k + v_k => \mathrm{z}_k = x_k + v_k \tag{3.4}$$

$$P^-{}_k = AP_{k-1}A^T + Q \tag{3.5}$$

$$k_k = P^-{}_k H^T (HP^-{}_k H^T + R)^{-1} \tag{3.6}$$

$$\hat{x}_k = \hat{x}_k^- + k_k (z_k - H\hat{x}_k{}^-) \tag{3.7}$$

$$P_k = (I - k_k H) P^-{}_k \tag{3.8}$$

x(k) = n x1 state vector,

z(k) = i x 1 measurement vector,

u(k) = r x 1 deterministic input vector,

A(k) = n x r time-varying input coupling matrix,

H(k) = t x n time-varying measurement sensitivity matrix,

B(k) = i x r time-varying output coupling matrix,

w(k) = r x 1 zero-mean uncorrelated “plant noise” process,

v(k) = i x 1 zero-mean uncorrelated “measurement noise” process

P(k) = Covariance Matrix

k(k) = Kalman Gain

R(k) = Measurement Noise Covariance

Q(k) = Process Noise Covariance

$\hat{x}_k$ = The Estimate State Vector

I(k) = Identity Matrix

Because we don't have any control signal u(k), we have accepted this value as "0".
To create the measurement matrix *H,* the real position, the bias values of satellite and the fault values are required. The generally needed structure to create the matrix *H* is shown in Figure 1.
Accordingly, the created model is shown below. [18, 19, 22, and 23]

$$\begin{bmatrix} x_{GNSS} \\ y_{GNSS} \\ z_{GNSS} \\ t_{GNSS} \end{bmatrix} = \begin{bmatrix} x & + & x_{\dot{I}.....BiasGNSS} \\ y & + & y_{\dot{I}.....BiasGNSS} \\ z & + & z_{\dot{I}.....BiasGNSS} \\ t & + & t_{\dot{I}.....BiasGNSS} \end{bmatrix} + \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix}$$

Figure 3.2 The measurement matrix, H

The values of X, Y, Z and t are the real position values of GNSS receiver. However, the values of $t_{\dot{I}.....BiasGNSS}$, $y_{\dot{I}.....BiasGNSS}$, $z_{\dot{I}.....BiasGNSS}$ and $t_{\dot{I}.....BiasGNSS}$ are errors which are composed of the position and time differences. When satellites send their own information about positions due to the atmospheric conditions and the relative movement of Earth and satellites, the differences of signal speed, even with the very small amount, occurs. Then, each signal being sent will have some small differences. In this case, it will be required to calculate the accuracy of the signal by considering these errors. v1, v2, v3 and v4 values are measurement noises. [22, 23]

H, the measurement matrix is considered in our model as a matrix of size [4x20]. These modes for each GNSS are shown in Table 3.1

$H_{GPS} =$	$\begin{pmatrix} 1&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&1&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&1&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&1&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0 \end{pmatrix}$
$H_{GLONASS} =$	$\begin{pmatrix} 1&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0 \end{pmatrix}$
$H_{GALİLEO} =$	$\begin{pmatrix} 1&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0 \end{pmatrix}$
$H_{COMPASS} =$	$\begin{pmatrix} 1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0 \\ 0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0 \\ 0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0 \\ 0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1 \end{pmatrix}$

Table 3.1 (The Measurement Matrix) One matrix for each GNSS

In our model, a state transient matrix is defined as an identity matrix because the system has low dynamics. *A* state transient matrix which is described as [20x20] in this thesıs is given in Table 3.2.

$A_{GNSS} =$	$\begin{pmatrix} 1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1 \end{pmatrix}$

Table 3.2 *A:* state transition matrix

Finally, it is required to define x_k the state matrix that is formed as [20x1].

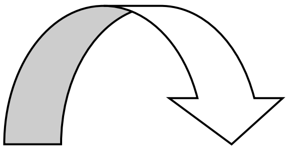
$x_k =$	$\begin{pmatrix} x \\ y \\ z \\ t \\ x_{GPSBias} \\ y_{GPSBias} \\ z_{GPSBias} \\ t_{GPSBias} \\ x_{GLONASSBias} \\ y_{GLONASSBias} \\ z_{GLONASSBias} \\ t_{GLONASSBias} \\ x_{GALİLEOBias} \\ y_{GALİLEOBias} \\ z_{GALİLEOBias} \\ t_{GALİLEOBias} \\ x_{COMPASSBias} \\ y_{COMPASSBias} \\ z_{COMPASSBias} \\ t_{COMPASSBias} \end{pmatrix}$

Table 3.3 The state vector definition

The position values of the receiver are supposed constant in this model. But the different position error values occur at the receiver because of the own errors of each satellite system. These errors are defined as bias values. On the model, it is required that the position values are analyzed with the bias values.

All the required inputs for the model are given in Table 3.1, Table 3.2 and Table 3.3. Finally, we suppose very small values of noises at the beginning of our sımulatıon.

While analyzing our model, standard Kalman filter is considered. So the calculated values on Prediction/Time Update are used in the forms of Correction / Measurement Update. Then, the calculated values on Correction / Measurement Update are put in Prediction/Time Update to guarantee the recursive performance. So for each K moment, the calculated output will be a new input for the next moment (K+1). The Kalman filter cycle that is explaining this situation is shown in Table 3.4



Prediction/Time Update	Correction/Measurement Update
1)Previous State Prediction	**1)**Kalman Gain
$\hat{x}_k^{-} = A\hat{x}_{k-1} + w_{k-1}$	$k_k = p^{-}{}_{k} H^T (Hp^{-}{}_{k} H^T + R)^{-1}$
2) Estimates Error Covariance	**2)** z_k , Estimates Measurement Location
$p^{-}{}_{k} = Ap_{k-1}A^T + Q$	$\hat{x}_k = \hat{x}_k^{-} + k_k(z_k - H\hat{x}_k^{-})$
	3) Error Covariance Update
	$p_k = (I - k_k H)\, p^{-}{}_{k}$

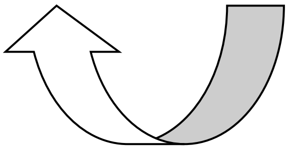


Table 3.4 Kalman filter cycle [18]

3.2 Simulation of our model using Matlab™

3.2.1. Scenarios Create and Run

For this created model, the values of the real signal are not always used, some scenarios have been made up just to show the accuracy of the approach.

In this model, each scenario is formed by getting imaginary bad or deception signal from the outside. To give the imaginary deception signal, we have selected the GPS. We have to note that any other GNSS may be also selected.

According to this situation, three different responses may be given the system were analyzed with three different scenarios on Matlab™ and then the outputs were evaluated.

These three responses are;

- The Normal Condition
- Glitch and without Reject Condition
- Glitch and Reject Condition

As expressed in previous chapters, the aim of this study is to show the system is capable of defending against disorder, confused or deception signals.

Generally to evaluate the system, in this simulation we are trying to affect it by deceiving the values of position and time. The actual case in here is to disturb the position time accuracy to prevent the accurate system to make its tasks.

In our simulation, to deceive the system, the value of Glitch was randomly selected to be 300 m. Thus, any another value can be selected. Then, four values were analyzed in each scenario, these are:

- Measurement Values of GNSS
- All GNSS Bias Estimate Error
- Covariance matrix
- Errors values according to the real X, Y, Z and t (time) position of receiver

3.2.2. Scenarios

3.2.2.1. The Working Strategy of Scenarios

1. A dynamic is developed and initialized for the fusion of multi-GNSS systems. Kalman filter equations are initialized.
2. Position and time measurements from multi-GNSS receivers are collected
3. Innovation to state estimations due to measurements is calculated. If there is too much discrepancy between the innovations size with respect to its covariance the measurement is rejected.
4. Accepted measurements are used to update state estimates according to Kalman filter equations and covariance matrix.

3.2.2.2. Scenario 1 (Normal Condition)

In Scenario 1, it is supposed that all values are seen as set point values without any attack or deception.

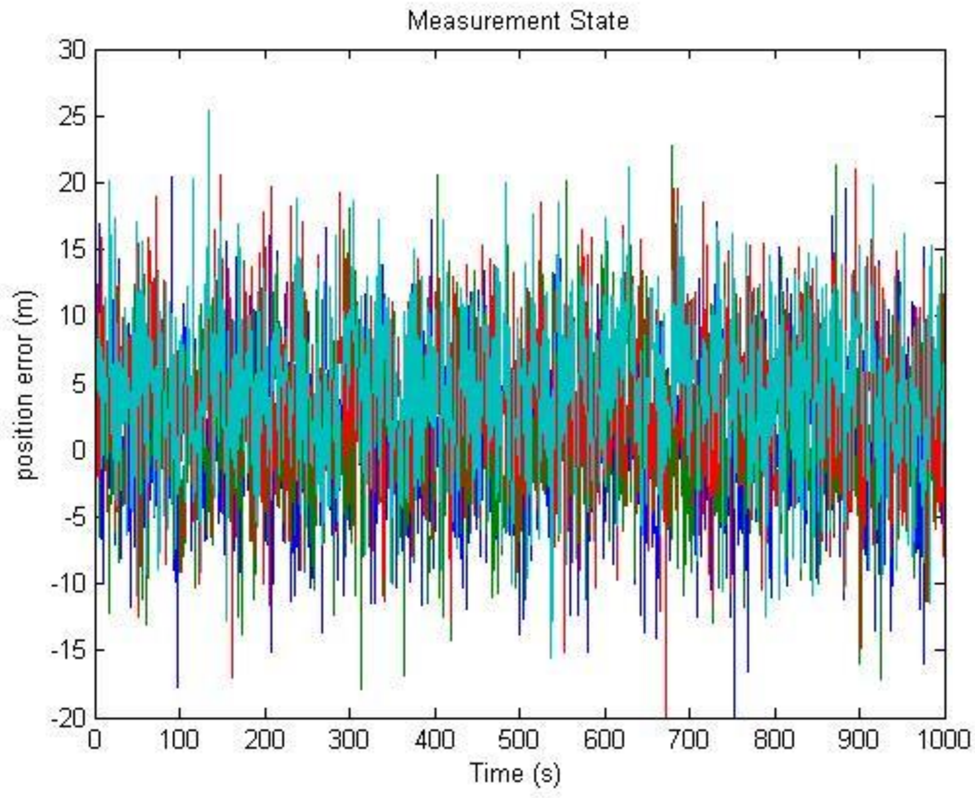


Figure 3.3 GNSS Measurement State

Firstly the system's errors are controlled by the system can create a solution by doing error analyzes.

The measurement state values of GNSS are shown in Figure 3.3. We can observe four measurements of the system, they are constant, describing nearly the same information and working without any signal disorder, confusion or deception. At this point, the system shows the measurement which was already taken without filtering or rejecting.

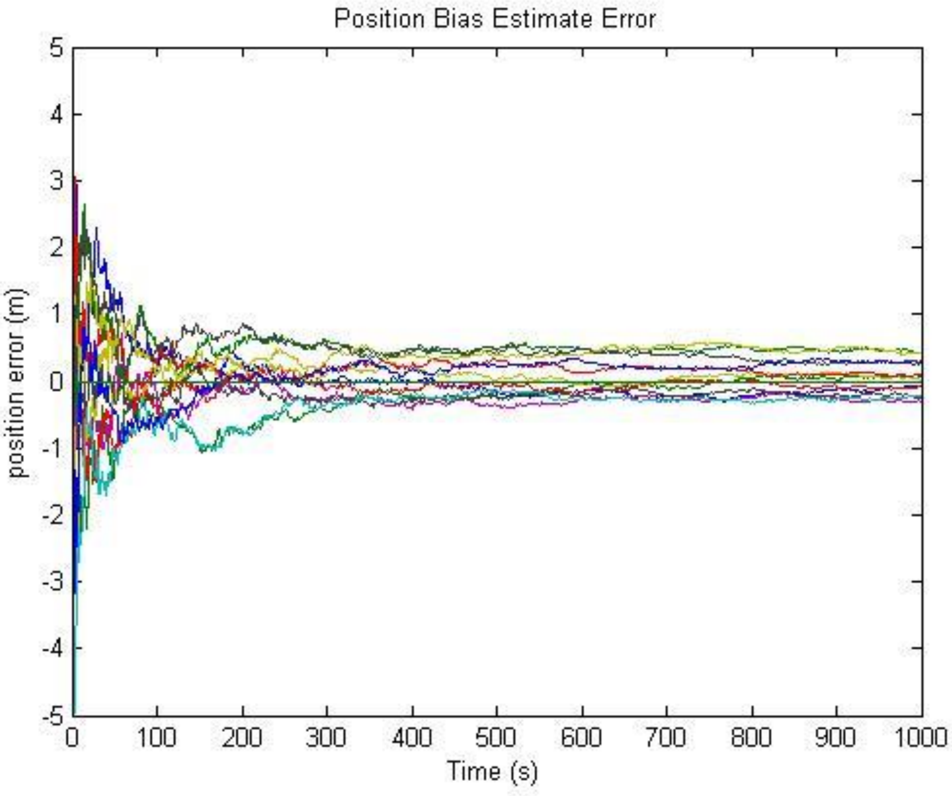


Figure 3.4 All GNSS Bias Estimate Error

If the measurement values are in normal condition, all GNSS bias estimate error values can be normal as shown in Figure 3.4.

The errors of x bias position of GNSS are shown in Figure 3.4. In this case, while the errors of all GNSS are high at the first occurrence time, the errors rate decrease with time and converge towards zero. But it cannot ever be zero.

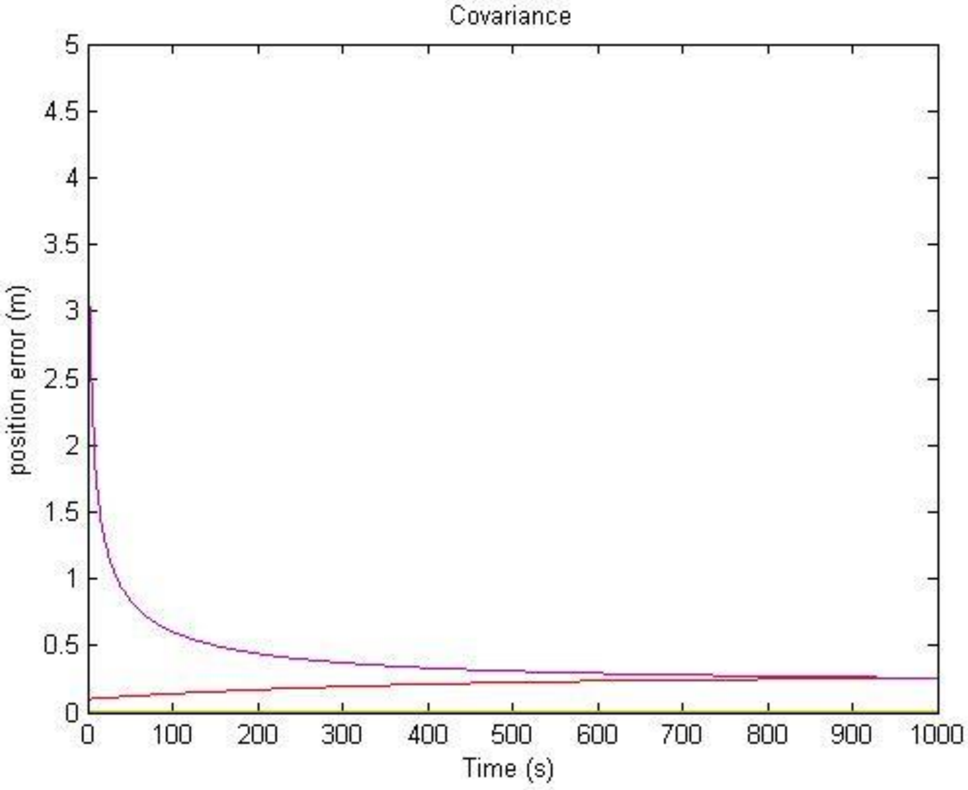


Figure 3.5 Covariance Matrix (covariance values of all 20 variables in the state vector)

In Figure 3.5 All GNSS Bias Estimate Error is a purple line and Receiver estimate error is a red line.

Without any spoofing attack to the system, the range of error measurement defined in covariance matrix doesn't make any deviation in parallel with all GNSS bias estimate error and it appears to regulate the system's errors

According to the analysis done in Figure 3.5, Kalman Filter Algorithm was executed to the prediction method successfully.

The covariance matrix which is used to verify the errors of GNSS bias prediction is shown in Figure 3.5. The covariance matrix that was designed for the model is shown how much error according to the measurements received.

According to Figure 3.5, we can learn the error degree of estimates through the covariance matrix.

It is easy to note that the covariance values are decreasing in parallel with the reduction rate of errors at the position values. When the distance error values didn't start from 3m, then continued at 0.5m intervals. Figure 3.5 illustrates the exchange graph of the first error value to be given the covariance matrix.

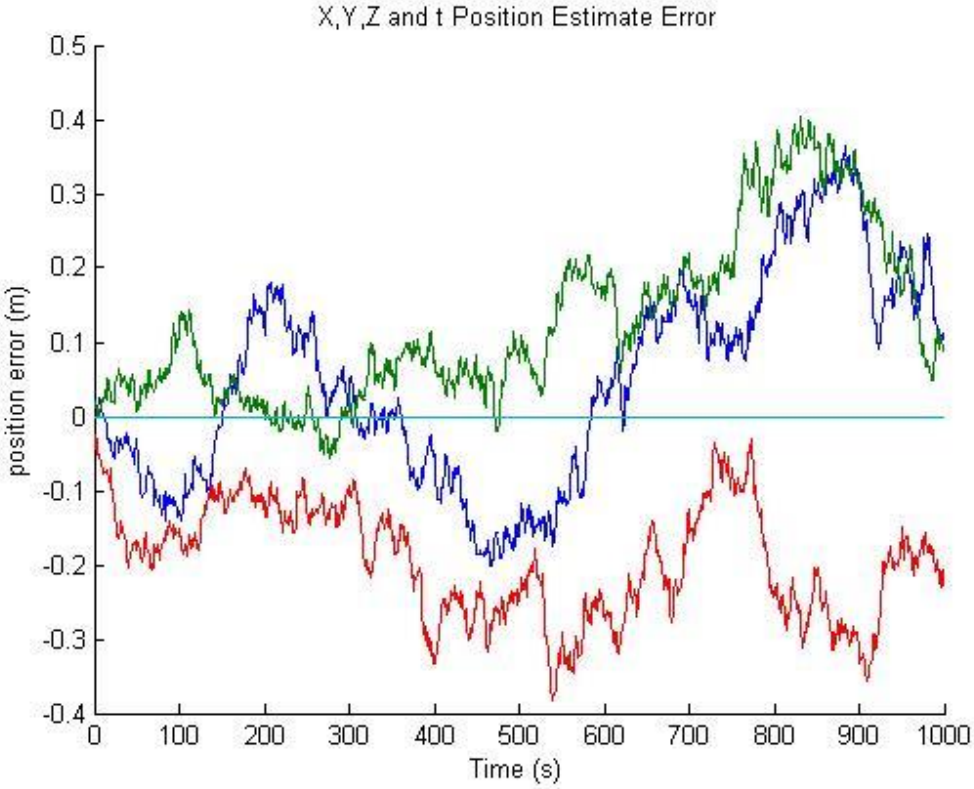


Figure 3.6 Receiver estimate errors on X (Blue), Y (Red), Z (Green) and time (Cyan) curves respectively

If there is not any error of the system, the errors of the receiver on X, Y, Z position and t (time) are shown in a normal condition in Figure 3.6. The average of X, Y, Z receiver position is between 0.25m and 0.5m and this is an acceptable range.

As the model is supposed to be linear and the time error is very small (that is caused by the receiver which is used to move slowly). The time error, as it is illustrated in Figure 3.6, is following a value close to zero.

To calculate, we use the following equation;

$$t' = t_{satalliteclock} - t_{receiverclock} \tag{3.9}$$

t' = Time Error

$t_{satalliteclock}$ =Satellite Clock

$t_{receiverclock}$ = Receiver Clock

3.2.2.3. Scenario 2 (Glitch and Without Reject Condition)

This scenario is provided to mix the GPS by sending a deception signal to the system. But, we suppose that the system doesn’t give any response (reject or without reject) against to this situation for monitoring a large increase in the rate of error as a result of this case.

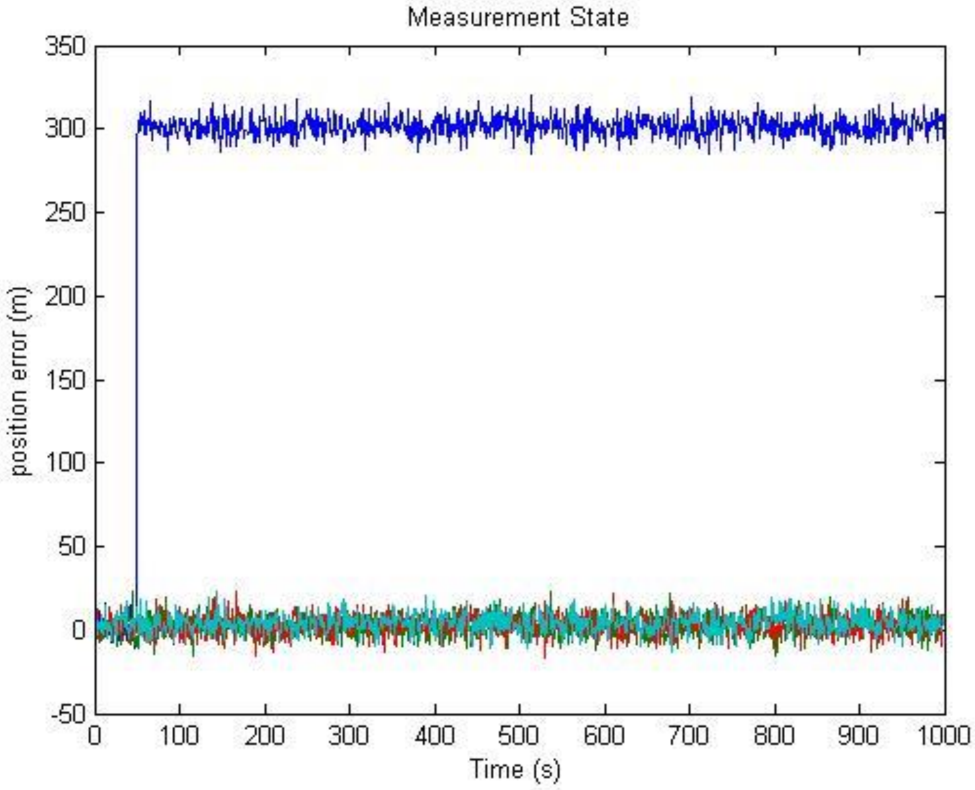


Figure 3.7 GNSS Measurement State

As shown in Figure 3.7, according to the model, created there is an error in the system as a result of the measurement. In this situation, the system creates incorrect measurement and it is shown as position and time error of receiver. According to Figure 3.7, the perceived output measurement stay the same and the distorted GPS signal appears in the range of 300 m. Because the values taken are measured by the system so any correction is not done.

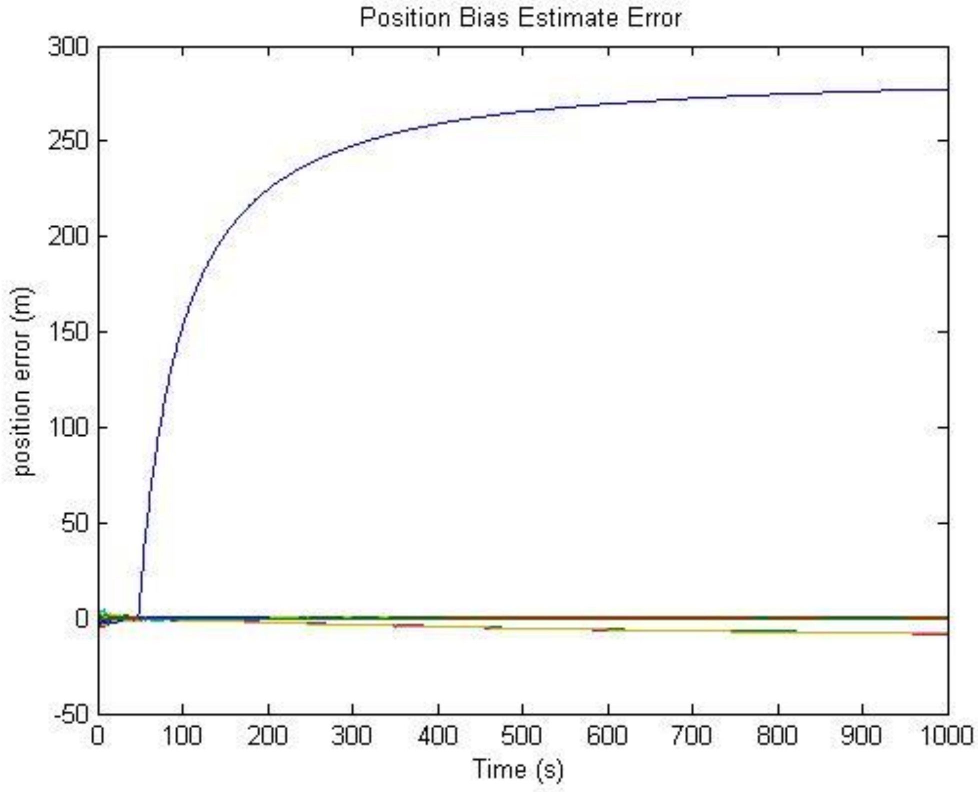


Figure 3.8 All GNSS Bias Estimate Error

As shown in Figure 3.8, to begin producing incorrect results of the measurement will be seen on the deviation graph of All GNSS Bias Estimate Error. At the beginning of the illustrated curve in Figure 3.8, the GNSS bias estimated error remains zero for a while after applying the error to the GPS signal. Then, it was increased to 300m of distance error. Herein is meant according to the situation, 300 m bias error given to X position is noticed by the system but it is accepted without rejection.

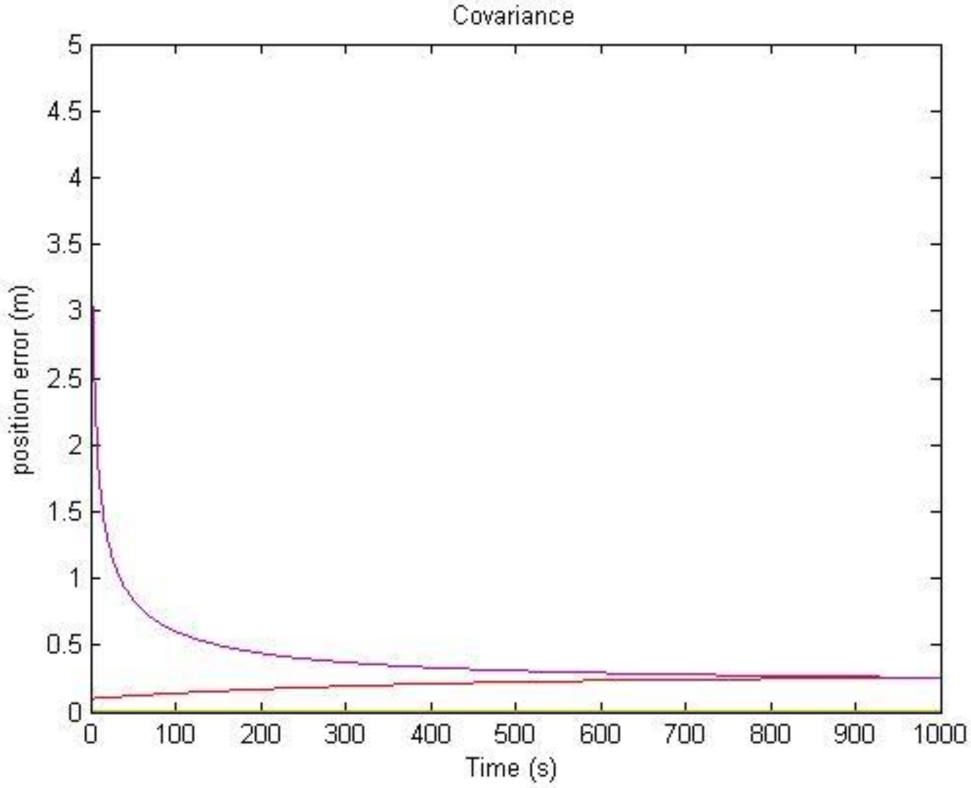


Figure 3.9 Covariance Matrix (covariance values of all 20 variables in the state vector)

Because we don't want to reject any error value on the covariance matrix, it is shown to continue to regulate the GPS errors. When the Covariance Matrix is examined in Figure 3.9, it is seen that the perceived covariance matrix to this situation is normal and it stays in the same location as long as any refusal command for this situation is coming from outside. Actually, this situation is incompatible with the system model. Thus, it is observed to continue in the circumstances where the error signal in the system is not rejected.

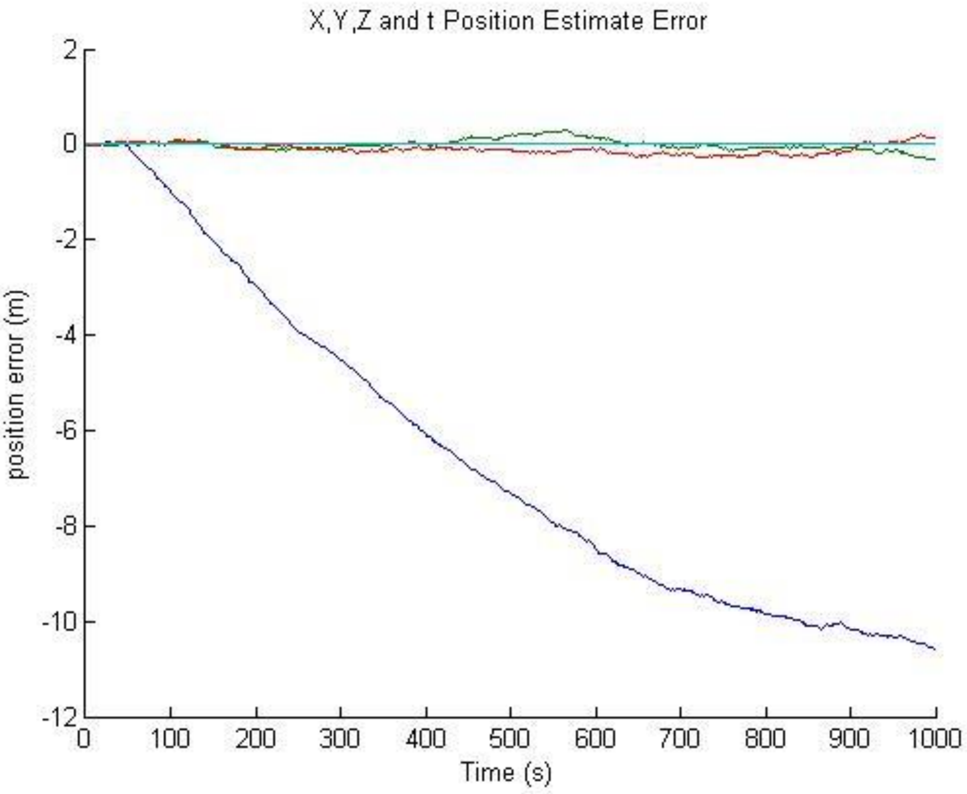


Figure 3.10 Receiver estimate errors on X (Blue), Y (Red), Z (Green) and time (Cyan) curves respectively

When the error detected in the measurement results are detected, if the system doesn't pass the reject position, it will be seen the handle of any position value as shown in Figure 3.7 that is the graph of X, Y, Z and t (time) Receiver Estimate Error. Only X position deviates because the model gave the error to X position.

As it is shown in Figure 3.10. After achieving the last cited mixing, the error rate is increased in the real position of the receiver (especially on X) and the non-acceptable distance error appears as a result of the separation of the GPS signal from the other GNSS. As shown on the graph above, X position is changed by the error value that we have given according to time.

3.2.2.4. Scenario 3 (Glitch and Reject Condition)

In this section in accordance with the created scenario, this section describes the deception signals to be detected by the system. It is illustrating how to detect the spoofing signal by the system and how to keep it out of this signal when doing the measurement by the system.

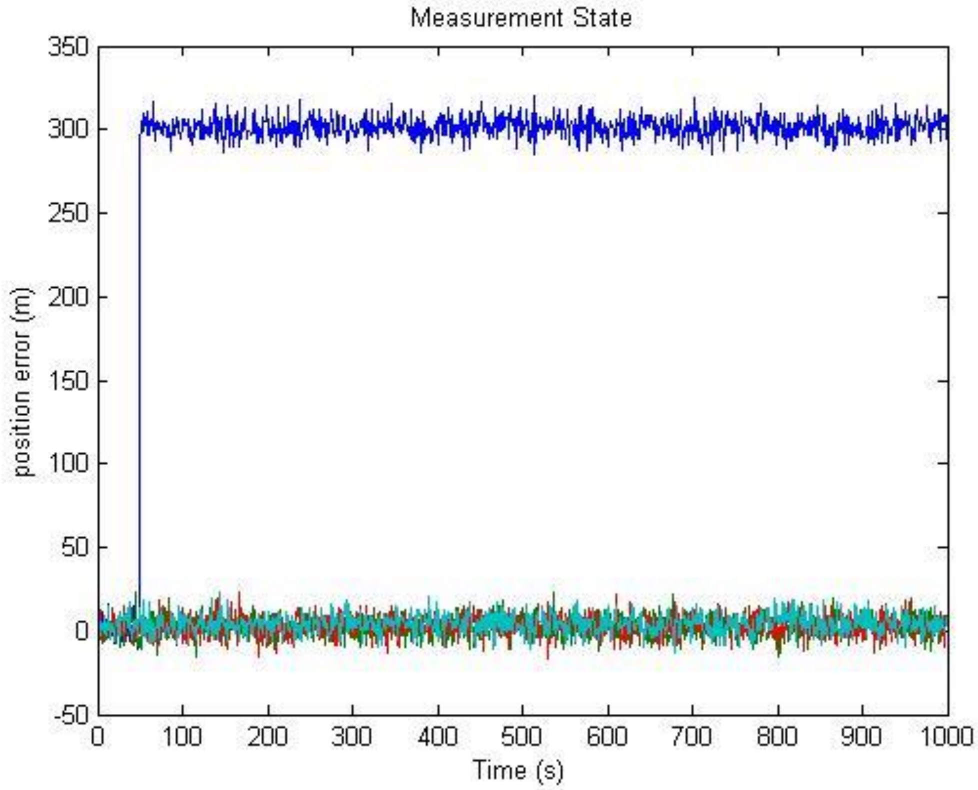


Figure 3.11 GNSS Measurement State

All the position measurements from the GNSS, blue track is the x- position from the spoofed GPS signal, the others are approximately same.

Finally, it can be examined on Figure 3.11 that Measurement State remains the same and GPS signals works in following 300 mt Because, the aim here is not to detect and reject the system errors, to shows all GNSS signal.

As seen here, although we broke GPS signal and showed it as incorrect of 300 m, the system shows the distance values of all GNSS.

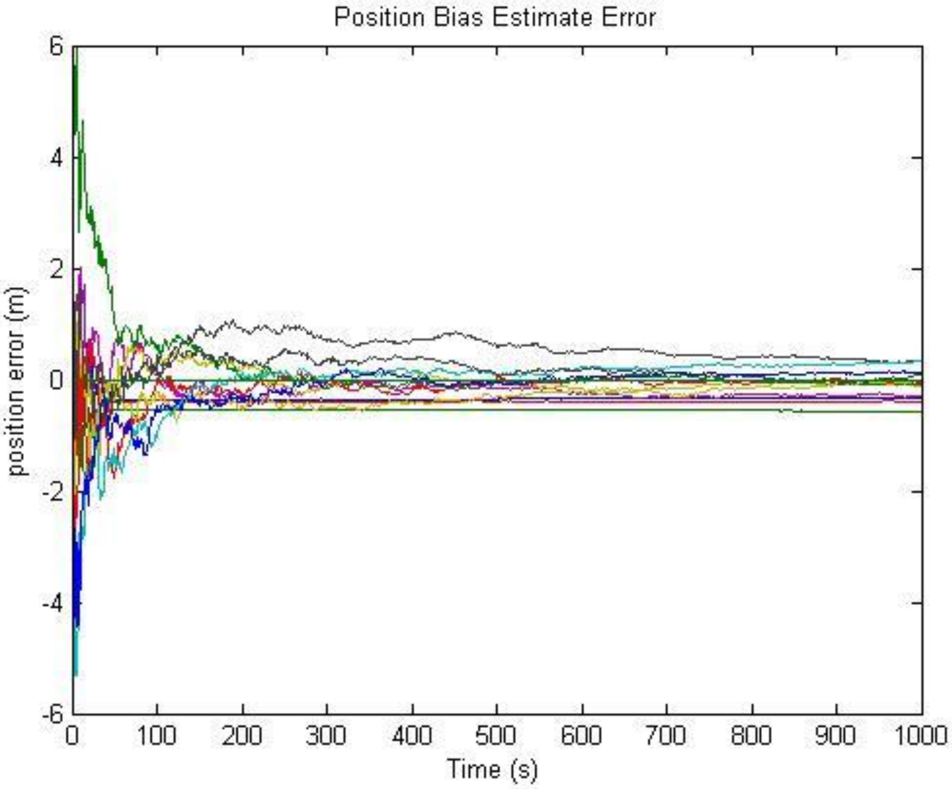


Figure 3.12 All GNSS Bias Estimate Error (estimation error of the last 16 variables in the state vector)

As shown in Figure 3.12, the faulty data entered to the system are noticed by the system and interfered. And as a result, GPS position data has given virtual error are hindered and rejected by the system.

According to Figure 3.12, the received GPS signal was accurate at the first stage when there is no spoofing. It could be also noted that the system has kept its accuracy during the spoofing stage as the spoofing signal is rejected as a stable. The spoofing signal is analyzed in the filter, and it was rejected when the spoofing was understood by the system.

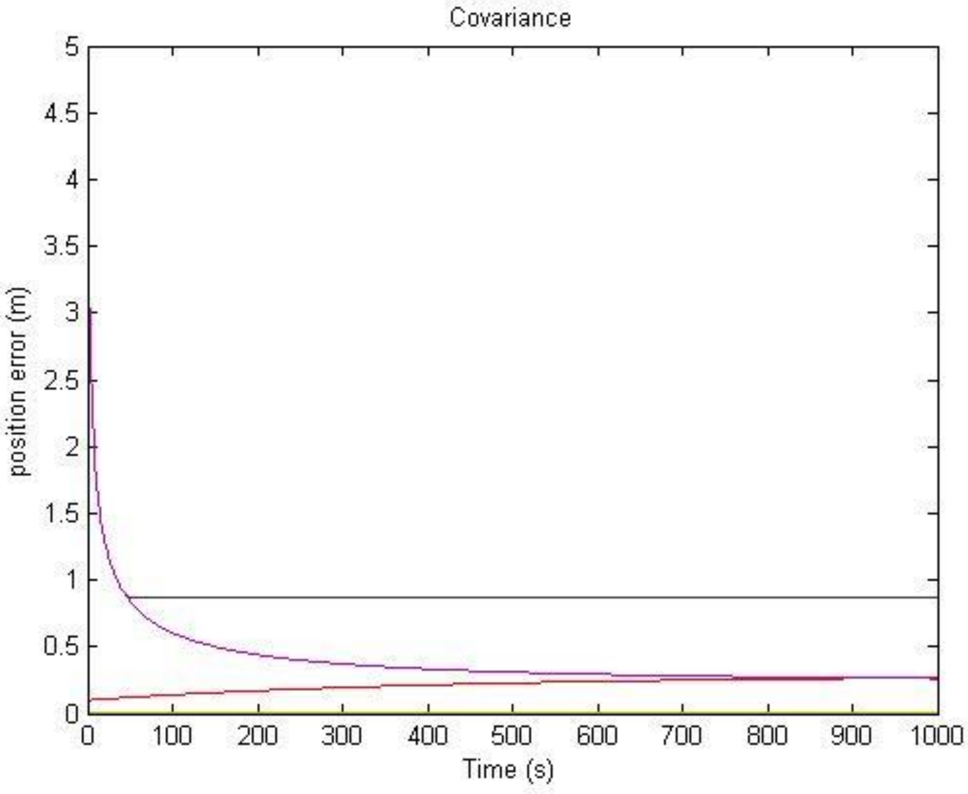


Figure 3.13 Covariance Matrix (covariance values of all 20 variables in the state vector)

Also to regulate the incorrect data of GPS which is rejected by the system and blocked by the covariance matrix for avoiding the system mix.

When we examine the Figure 3.9, we may mention that the covariance matrix remains indifferent as the spoofing signal is not detected. However, in this case, the spoofing detected and the GPS signal is rejected therefore the other GNSS covariance values stay the same in Fig.3.13 shown by the purple trace.

According to Figure 3.13, after rejecting the error signal, covariance values for the GPS bias states does not decrease as we don’t use any GPS information during the spoofing.

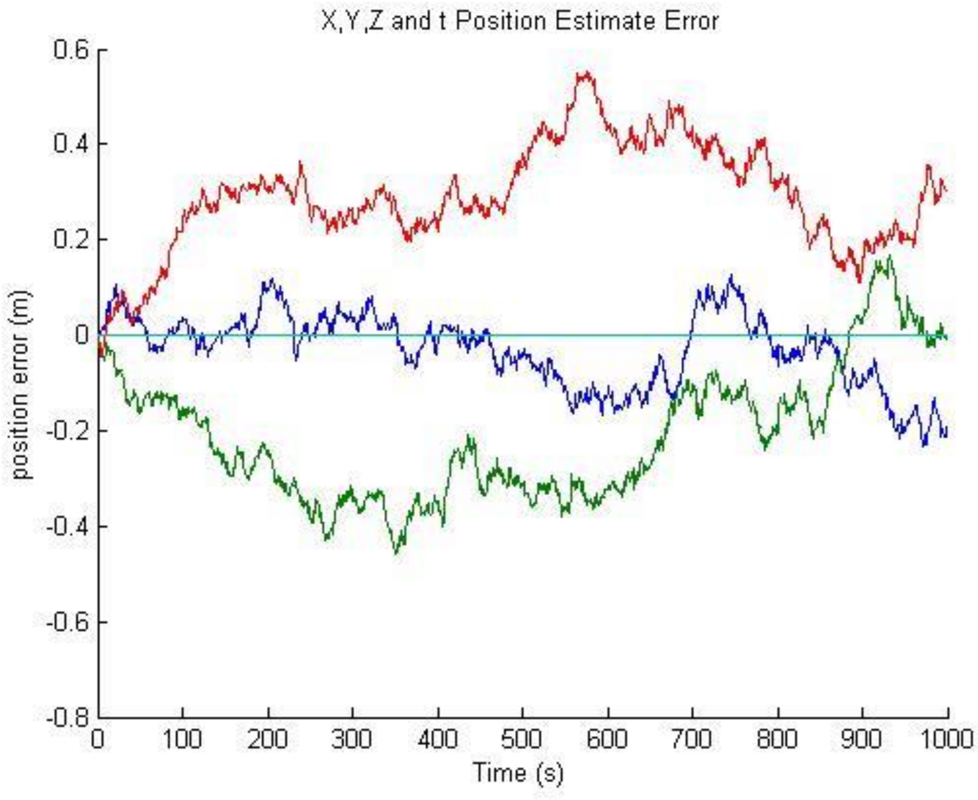


Figure 3.14 Receiver estimate errors on X (Blue), Y (Red), Z (Green) and time (Cyan) curves respectively

As shown in Figure 3.14, after the signal received by measurement is understood as spoofing, this faulty signal is blocked to enter the position error of receiver rejected. In Figure 3.14, after achieving the spoofing, the changes of GPS distance values are filtered by the system and they are not included in the calculation of the receiver position. This result shows that the system is identical with the normal condition and continuously working in stable mode by decomposing errors.

CONCLUSION AND SUGGESTION

Conclusion

GNSS systems were explained in the first part of this thesis. The working principles of these systems were handled in a detailed way. The required analyzes and the overall map of the system were illustrated. Four GNSS systems were handled. But, we have to note that other GNSS systems flying over the world have the same working principles like these four cited systems.

The model of our linear system was clarified in the second chapter. Kalman filter was used to be the structure of our model. This approach was explained in detail in that chapter as it was elaborated how to make modeling with this method.

The built model was simulated by using Matlab™. Where; three scenarios were prepared to clear up the aim of this thesis.

In the first scenario;

The exit signals of the model under normal conditions were analyzed. According to the following conditions;

- The approximate position curves obtained from GNSSs were also observed and the estimation errors were identified. They were shrinking in parallel with the covariance matrix, so that means the model is consistent with the measurement data
- The measurement values of GNSSs were observed. They remained at the same intervals under normal conditions and didn't show variability with big errors.
- The error on X, Y, Z coordinates of the receiver was analyzed under normal conditions and the estimate state variables were analyzed. So little error at the exit signals was observed.

In the second scenario;

The exit signals were spoiled by being mixed as if a spoofing signal may come from the outside to one of our GNSS systems and the alterations applied to the system were analyzed before this error signal wasn’t rejected by the implementation. According to this situation;

- The approximate position distances of GNSSs were observed under these conditions and the bias error interval of GNSSs was observed that increased up to the 300 meters distance. Covariance matrix didn’t identify any alteration under this condition.
- The measurement values of GNSSs were observed. They were measured by keeping 300 meters distance of system as a given error under this condition.
- So that we can analyze the error on X, Y, Z coordinates of the receiver, X coordinate was given with three hundred meter spoofing signal and the conditions system didn’t take any precaution against this spoofing signal. It was observed that the error rate increased under this condition.

In the third scenario;

The output signals were spoiled by a spoofing signal would come from the outside to one of four GNSS systems. No, prior information was provided to the model for the spoofing signal. The results were analyzed under these conditions,

- As the spoofing signal was too much out of the boundary set by the covariance matrix, it was rejected immediately when the spoofing starts and it was not included in the fusion process. As the spoofing signal is not injected into the output signal, estimation errors are aligned with the covariance values. The estimation error change is compatible with the covariance.
- The measurement values of GNSSs remained the same under this condition and continued to show 300-meter offset as in scenario 2.
- It was observed that the estimated error in X, Y, Z coordinates of the receiver was approximately same with the first scenario under normal conditions.

Consequently, the model we used has protected the platform against the spoofing signal coming from the outside.

Evaluation and Future Studies

The values received as a result of Matlab™ implementation are enough to prove the efficiency of our approach.

However, knowing that we have modeled virtual signals in this study and as we have always the possibility of receiving spoofing signals in real life under different conditions faces us with the truth that we need a stronger structure in the next phases.

Therefore, in future studies, in order to generalize our result, we plan to use extended Kalman filter, to track non-linear signals while getting the distance and space location data from GNSSs. We are going to simulate our models in a real-time structure by running it on Matlab™.

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