İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

INTEGRATION OF HELICOPTER AIR DATA SYSTEM WITH GLOBAL POSITIONING SYSTEM USING KALMAN FILTER

M.Sc. Thesis by
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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

HELİKOPTER HAVA VERİLERİ SİSTEMİNİN KÜRESEL KONUMLANDIRMA SİSTEMİ İLE KALMAN SÜZGECİ TEMELİNDE TÜMLEŞTİRİLMESİ

YÜKSEK LİSANS TEZİ

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ÖNSÖZ

Bugünün havacılık sanayinde uçuş güvenliği en önemli konu olmuştur. Her yeni gün yeni bir uçuş emniyeti düzenlemesi ortaya çıkmaktadır veya eski düzenlemelere bazı sınırlamalar getirilmektedir. Bu güvenlik gereklerini gerekliliklerini yerine getirmek için doğru ve uygun maliyetli bir çözüm bulmanın en önemli yolu ise tümleşik seyrüsefer sistemlerinin kullanılmasıdır.

Seyrüsefer bir hava aracı için bu kadar önem arz ediyor iken, son yıllarda seyrüsefer alanında atılım sayılabilecek bir gelişmeden bahsetmeden de olmaz; bu gelişme Global Konumlandırma Sistemidir(GPS). 1970lerde başlayan atılım 1 Mayıs 2000 de askeri kullanıcılar hariç diğer tüm sivil GPS kullanıcılarda 100 metre konum hatasına sebep olan SA(Seçmeli Kullanılırlık) hatasının ortadan kaldırılması ile büyük bir ivme kazanmıştır. Bu teknoloji ile ilgili araştırmalar ve kullanım alanları büyük bir artış göstermiştir.

Çalışmamızın birinci kısmında konum hatası büyük oranda azaltılmış olan GPS alıcılarının hala gürültü içeren konum bilgileri Kalman Filtresi yardımı ile daha da azaltılmaya çalışılmıştır. Bunu yaparken uydu mesafeleri yöntemi kullanılmıştır.

Uçakların konum ve hız bilgilerinin doğru bulunması uçuş kontrol ve seyrüsefer sistemleri için hayati önem taşımaktadır. Ayrıca bir hava aracı için rüzgar hızının uçuş güvenliği ve yönetimi açısından önemi de çok büyüktür. Beklenmedik durumlarda oluşan yüksek rüzgar hızları, uçuş güvenliği ve kontrolü açısından bilinmesi gereken bir parametredir. Bu çalışmanın ikinci kısmında yüksek doğrulukta hız ve konum bilgisi ve yüksek doğrulukta rüzgar hızının bulunabilmesi amacıyla Hava Verileri Sistemi(ADS) ile Global Konumlandırma Sistemi (GPS) Kalman Filtresi temelinde tümleştirilmiş ve incelenmiştir.

Bu çalışmada GPS konum ve hız verilerinin iyileştirilmesi ve Hava Verileri Sistemi ile Global Konumlandırma Sistemi hız ve konum bilgileri kullanılarak yüksek doğrulukta ve yüksek ölçüm frekansına sahip bir tümleştirilmiş seyrüsefer sistemi elde edilmesi amaçlanmıştır.

Bu çalışma için öncelikle bilgi ve tecrübesini benimle paylaşan danışman hocam Prof.Dr. Çingiz HACIYEV' e, benden her türlü desteği bir an olsun esirgemeyen sevgili aileme, bilimsel ve teknik sinerji oluşmasında katkısı olmuş tüm meslek arkadaşlarım ve dostlarıma teşekkürü bir borç bilirim.

Mayıs 2006 Taner Mutlu

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ABBREVIATIONS

ASCII : American Standard Code for Information Interchange
ARM : Advanced Risc Machine
MIPS : Million Instructions Per Second
MCU : Micro Controller Unit
ADC : Air Data Computer
ADS : Air Data System
AHRS : Attiude and Heading Reference System
ASI : Airspeed indicator
VSI : Vertical speed indicator
ALT. : Altitude indicator
ATC : Air Traffic Control
SA : Selective Availability
CRC : Cyclic Redundancy Check
NMEA : The National Marine Electronics Association
BPSK : Binary Phase Shift Key Modulation
Bps : Bits Per Second
C/A : Coarse Acquisiton
LLA : Longitude Latitude Altitude
ECEF : Eart-Centric Earth-Fixed
GPS : Global Positioning System
TAS : True Air Speed
GNSS : Global Navigation Satellite System
CPU : Central Processing Unit
DGPS : Differential Global Positioning System
I-DGPS : Inverse DGPS
VOR : VHF Omni Range
INS : Inertial Navigation System
INU : Inertial Navigation Unit
IMU : Inertial Measurement Unit
DoD : Department of Defence
GLONASS : Global Navigation Satellite System
LORAN : Long Range Navigation System
DR : Dead Reckoning
KF : Kalman Filter
NAVSTAR : Navigation System with Time and Ranging
RADAR : Radio Detecting and Ranging
DOP : Dilution of Precision
PDOP : Position Dilution of Precision
HDOP : Horizontal Dilution of Precision
VDOP : Vertical Dilution of Precision
GDOP : Geometric Dilution of Precision
TDOP : Time Dilution of Precision
RDOP : Relative Dilution of Precision

RMS : Root Mean Square
DSP : Digital Signal Processor
GPIO : General Purpose Input/Output
GIS : Geographic Information Sytem
GMT : Greenwitch Mean Time
HAE : Height Above Ellipsoid
MSL : Height Above Mean Sea Level
Hz : Hertz
EMC : Electromagnetic Compatibility
EMI : Electromagnetic Interference

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SYMBOL LIST

V_x, V_y, V_z	: Speeds at directions X, Y, Z
$V_{adsx}, V_{adsy}, V_{adsz}$	: True air data speeds at directions X, Y, Z
$V_{gpsx}, V_{gpsy}, V_{gpsz}$	: GPS speeds at directions X, Y and Z
$V_{eadsx}, V_{eadsy}, V_{eadsz}$	: True air data speed errors at directions X, Y, Z
$V_{egpsx}, V_{egpsy}, V_{egpsz}$	: GPS speed errors at directions X, Y and Z
$V_{eadsgx}, V_{eadsgy}, V_{eadsgz}$	: Simulated air data speed errors at directions X, Y, Z
$X_{eadsg}, Y_{eadsg}, Z_{eadsg}$	: Simulated air data position errors at directions X, Y, Z
$X_{ads}, Y_{ads}, Z_{ads}$	: True air data positions derived from speeds at directions X, Y, Z
$X_{eads}, Y_{eads}, Z_{eads}$	: True air data position errors derived from speeds at directions X, Y, Z
$\hat{V}_{adsx}, \hat{V}_{adsy}, \hat{V}_{adsz}$	: Estimated true air data system speeds at directions X, Y, Z
$\hat{V}_{eadsx}, \hat{V}_{eadsy}, \hat{V}_{eadsz}$	: Estimated true air data system speed errors at directions X, Y, Z
$\hat{X}_{ads}, \hat{Y}_{ads}, \hat{Z}_{ads}$	: Estimated true air data system positions at directions X, Y, Z
$\hat{X}_{eads}, \hat{Y}_{eads}, \hat{Z}_{eads}$	: Estimated true air data system position errors at directions X, Y, Z
$\sigma_{V_{gpsx}}, \sigma_{V_{gpsy}}, \sigma_{V_{gpsz}}$	: Standard deviations of GPS speeds at directions X, Y and Z
$\sigma_{V_{adsx}}, \sigma_{V_{adsy}}, \sigma_{V_{adsz}}$	: Standard deviations of ADS speeds at directions X, Y and Z
$Var(V_x), Var(V_y), Var(V_z)$	: Variances of speeds at directions X, Y and Z
$Var(X), Var(Y), Var(Z)$	: Variances of speeds at directions X, Y and Z
A	: System Dynamics Matrix
λ	: Wave length
σ	: Standard deviation
τ_c	: Correlation time
ψ	: Azimuth angle
T	: Period
c	: Speed of Light
$\delta(k)$	: Kroenecker delta
$x(k)$	: System state matrix
$\phi(k+1,k)$	: System transfer matrix
$G(k+1,k)$	: System noise transfer matrix
$w(k)$	: Zero-mean Gauss noise vector
$H(k)$	: System observation matrix

E	: Statistical mean operator
$z(k)$	: Measurement observation vector
$P(k,k)$	: Extrapolation error correlation matrix
$K(k)$	: Kalman Filter Gain
$\Delta(k)$	: Innovation process
$\hat{x}(k,k)$	: Estimation vector of $x(k)$
$\hat{x}(k,k-1)$	: Extrapolation value vector
$Q(k)$	: System noise correlation matrix
$\beta_{V_{adsx}}, \beta_{V_{adsy}}, \beta_{V_{adsz}}$	: Inverse of air data speeds correlation times (X, Y, Z)
$\tau_{V_{adsx}}, \tau_{V_{adsy}}, \tau_{V_{adsz}}$	: Air data speeds correlation times (X, Y, Z)
u	: Flight speed in direction *X*(m/sec)
w	: Flight speed in direction *Z*(m/sec)
q	: Pitch angular speed(degree/sec)
θ	: Pitch angle(degree)
β	: Yaw angle(degree)
ϕ	: Roll angle(degree)
p	: Roll angular speed(degree/sec)
r	: Yaw angular speed(degree/sec)
α	: Angle of attack

HAVA VERİLERİ SİSTEMİ İLE GLOBAL KONUMLANDIRMA SİSTEMİNİN KALMAN FİLTERSİ TEMELİNDE TÜMLEŞTİRİLMESİ

ÖZET

Bu tezde hava araçları için büyük öneme sahip olan seyrüsefer sistemlerinin performanslarının iyileştirilmesi amaçlanmıştır. Daha güvenli seyir için seyrüsefer sistemlerinin konum ve hız gibi bilgileri yüksek doğrulukta sağlanması istenmektedir. Konum bulmada son yıllardaki en önemli gelişme uydu seyrüsefer sistemlerinin kullanılmaya başlanmasıdır. GPS, global ölçekteki ilk ve günümüzde tam anlamıyla çalışan tek seyrüsefer sistem olması sebebiyle önemlidir. Seyrüsefer sistemlerinde çığır açan bir diğer önemli gelişme de elektronikteki gelişmeler doğrultusunda işlemci hızlarındaki artıştır. Bunun seyrüseferde önemli olmasının sebebi gürültülü işaretlerin hatalarını azaltma amacıyla 1960larda geliştirilen Kalman Süzgecinin artık günümüz işlemcileriyle gerçek uygulamalarda kullanılabiliyor olmasıdır.

Tezimizin birinci kısmında 2000 yılında SA özelliği iptal edilerek 100m konum hatalarından 30m konum hata seviyelerine indirilen GPS hatalarının, Kalman Süzgeci temelinde uydu mesafeleri yöntemi kullanılarak, daha da azaltılması amaçlanmıştır. Bu amaç doğrultusunda bileşenlerini kullanarak kendi yaptığımız GPS alıcısı ile elde ettiğimiz değişik nitelikteki konum bilgilerini gerçek konum, anlık alıcı konumu ve uydu konumlarını elde etmek için kullandık. Kalman Süzgecinde de tamamen, ölçülmüş konum bilgileri kullandık. Üretici firma tarafından yatayda 13m, dikeyde 22m olan konum hatasını bu yöntem ile daha da azaltmayı hedefledik.

Tezimizin ikinci kısmında yüksek örnekleme frekansına ve düşük ölçme doğruluğuna sahip hava verileri sistemi ile düşük örnekleme frekansına ve ADS ye göre yüksek doğruluğa sahip GPS sisteminin Kalman Süzgeci temelinde tümleştirilmesi hedeflenmiştir. Böylece her iki sistemin de avantajlarına sahip bir seyrüsefer sistemi amaçlanmıştır. Hava verileri sisteminin elde ettiği hava hızı hatasının elde edilmesi ve KF yardımıyla minimize edilmesiyle aynı zamanda yüksek doğrulukta rüzgar hızının da elde edilmesi amaçlanmıştır.

INTEGRATION OF AIR DATA SYSTEM WITH GLOBAL POSITIONING SYSTEM USING KALMAN FILTER

ABSTRACT

This study is focused on the imrovement of the modern navigation systems. In aeronautics high precision is very essential. And a recent development has revolutionized the navigation systems; this development is the Global Positioning System. It has been actually used since 1980’s, however with high deviations to the non-authorized users. The SA error has been removed in year 2000 and civilian GPS users were able to access high accuracy GPS data. Another good news is the improvement in processor speed. Kalman Filter was theoretically improved in 1960’s, however it wasn’t practical due to slow processing speeds. Today an ARM MCU can process up to 200 MIPS, which makes Kalman Filters a reality.

In part one; GPS position measurements obtained from a GPS receiver, are improved using Kalman Filter based Satellite Distances method. The GPS receiver provides us with both available satellite positions and the position of the receiver. Using this information in the Kalman Filter a better position compared to the GPS receiver alone was aimed. The actual Horizontal position error is stated as 13m, and the vertical position error is stated as 22m by the GPS chip provider.

In part two the integration of two navigation systems ADS and GPS was aimed. ADS is a widely used navigation system which measures static and total air pressure and the air temperature. The modern ADS includes a ADC, which computes parameters like Mach Number, True Air Speed, Vertical Speed etc. Using these three measurements. ADS has high sampling frequency and poor accuracy, on the other hand, another navigation system GPS has high accuracy compared to ADS but lower sampling frequency (1Hz). Kalman Filter is used to integrate and minimize the errors of the two navigation systems. By this integration a navigation system with high sampling frequency and high accuracy is aimed. Another object is to calculate the wind speed with high accuracy, which is actually the error of Air Speed measured by the ADS.

1. INTRODUCTION

Navigation is the process of determining significant position, velocity, attitude, and time (PVAT) information relative to specified references. Guidance is the process of using navigation information to steer or maneuver in an intelligent way. Three types of navigation came to these days: celestial navigation, deduced reconnaissance, (commonly called dead reckoning), and pilotage. Today, modern airborne navigation systems are classified as either autonomous or position fixing, passive or active, stand-alone or aided, analog or digital. An autonomous passive system, such as an inertial guidance system, provides reasonably accurate instantaneous PVAT output with no dependence on any external man-made device or signal; that is, it is neither jammable nor capable of being sensed from outside the vehicle. Stand-alone navigation systems, on the other hand, usually require externally provided electro magnetic signals from ground-based radio navigation aids (NAVAIDS) or from space-based satellites [1].

Integrated navigation systems combine the best features of both autonomous and stand-alone systems and are not only capable of good short-term performance in the autonomous or stand-alone mode of operation, but also provide exceptional performance over extended periods of time when in the aided mode. Integration thus brings increased performance, improved reliability and system integrity, and of course increased complexity and cost [2]. Moreover, outputs of an integrated navigation system are digital, thus they are capable of being used by other resources of being transmitted without loss or distortion.

The new century's improvements in computer technology, and increased data processing rates brought the ability to improve the navigation systems of air vehicles in precision, correctness and reliability.

The integrated navigation systems concept with the application of the Kalman filter was a milestone, and we were witnesses to these improvements in the near past. A great amount of study has already been made about this issue. Many more seem to be observed in the future. As many of these studies were examined, and some useful information was reached.

In the paper [3] integrated navigation system issue has been discussed. In the paper it is stated that, with the demand from the aviation industry, Instrumental Landing Systems (ILS) tend to be improved. This could not only be through replacement with the Microwave Landing System (MLS), but also by integrating Global Positioning System to the ILS that is practically in service.

Due to the paper, the majority of current precision landing research has exploited stand-alone GPS receiver techniques. This paper, as an improvement, exploits the possibilities of using and Extended Kalman Filter (EKF) that integrates an Inertial Navigation System (INS), GPS, Barometric Altimeter, and Radar Altimeter for precision aircraft approaches. As a result, it is seen that Federal Aviation Authority (FAA) requirements for Category I and II approaches could be met through this new approach.

The work in the paper is conducted through a computer simulation. The simulation program is basically developed on Kalman filter algorithms. The plotted outputs are generated by the commercial software package MATLAB. In this manner, regarding the subject and the tools, this paper is very close to the issue discussed in this study [3].

In the paper [4] development of a Kalman filter for optimal combination of GPS, INS and Radar Altimeter data is presented. Due to the paper, being two independent navigation systems, GPS and INS have their own shortcomings when used in a stand-alone mode. The ever-growing drift in position accuracy of the INS, and the possible unavailability of the GPS signals are discussed. The author suggests that, these shortcomings would be eliminated, and each system's best performances combined through the Kalman filter.

The benefits of integrating GPS with a strapdown INS are significant. However, altitude accuracy can further be improved by integrating the GPS, baro-inertial loop aided strapdown INS, and radar altimeter data. An error model of the strapdown INS plays an important role in the development of a Kalman filter for optimal combination of navigation data provided by GPS, strapdown INS and radar altimeter.

Integrating the error models of each system with the use of the Kalman filter simulates this. The simulation results show an undeniable improvement in the demanded properties. The approach, tools and the data are identical to the ones in this study and the results are somehow in the same manner [4].

Another work on the integration of INS and GPS was done in [5] by a group of scientists at the Technical University of Darmstadt. The group named ‘High Precision Navigation’ showed some experimental effort to prove the improvement of navigation parameters in an integrated navigation system. The main tool was the Kalman filter as usual, but this time the attitude of the vehicle was monitored as shown in their paper dated 1994 [5].

NASA was also interested in the application of Kalman filter in the navigation systems. The need for the precision altitude determination at low altitude flight phases was the main issue. On a multi-sensor navigation suite, again using Kalman filter as the main tool for integrating navigation data from different origins, radar altimeter and INS data was used for selecting the most similar digital map profile in obtaining horizontal position.

A close subject was discussed by a working group of NASA and U.S. Army in 1993. The improvement of a terrain-referenced guidance system with the implementation of radar altimeter into the traditional navigation system by the help of the Kalman filter was exploited. Starting from mathematical models, this group was able to accomplish some flight tests and experiments on a Blackhawk Helicopter, as a navigation test bed [6,7].

There have been many studies on integrated navigation systems, and one which is closely related to our study, in this study both Air Data System and GPS has been used to obtain better navigation. In this study GPS is used to calibrate the inaccurate Air Data measurements. However the GPS samples are used to calibrate the ADS samples one-to-one. In this study no filtering approach has been used to minimize the error[26].

Starting from the famous paper of Kalman [8] dated 1960, many efforts could be found in the navigation improvements history, about Kalman filter and integrated navigation systems. This is a very rapid development, and the future trend seems to climb and accelerate about the integrated navigation systems. There are many articles in that field of science [9-19].

2. GLOBAL POSITIONING SYSTEM

The Global Positioning System is based on the US Department of Defense's NAVSTAR satellites. NAVSTAR (NAVigation Satellite Timing and Ranging) satellites permit users to determine their position in three dimensions anywhere on the earth. Additionally, time and velocity are also available. This service is free of charge and is provided 24 hours a day worldwide. The system is only slightly affected by the weather. When compared with other navigation systems, GPS is an order of magnitude improvement. For GIS, GPS makes the world your digitizer table. The GPS system is revolutionizing the practice of surveying and positioning. The GPS became fully operational on December 8, 1993.

2.1 GPS System Segments

There are three segments that make up the GPS system. They are Space, Control and User. Space Segment The Navstar satellites make up the space segment. 28 satellites inclined at 55° to the equator orbit the earth every 11 hours and 58 minutes at a height of 20,180 km on 6 different orbital planes (Figure 2.1). The spacing of satellites in orbit is arranged so that a minimum of five satellites will be in view to users worldwide. A minimum of three satellites is required to obtain your Latitude, Longitude and Time. Having a forth satellite in view permits the GPS receiver to compute altitude.

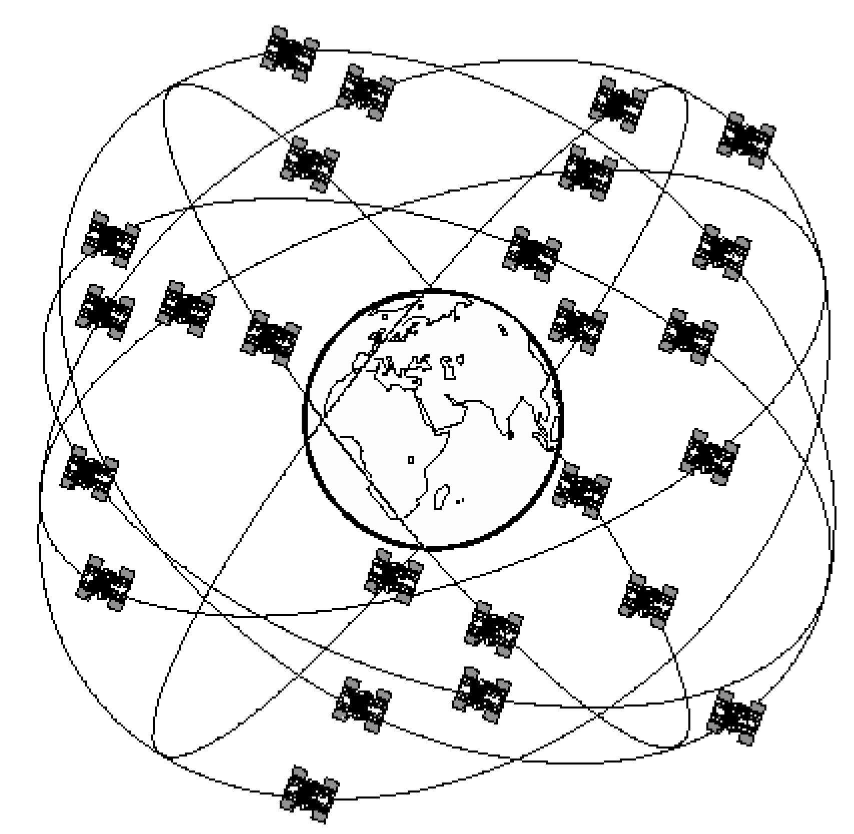

Figure 2.1: GPS satellites orbit the earth on 6 orbital planes

The satellites transmit time signals and data at a frequency of 1575.42 MHz. The minimum signal strength received on Earth is approx. -158dBW to -160dBW. The maximum power density on earth is 14.9 dB below receiver background noise (thermal noise floor).

Control Segment The control segment consists of five Monitor Stations (Hawaii, Kwajalein, Ascension Island, Diego Garcia and Colorado Springs) and three ground antennas, (Ascension Island, Diego Garcia, Kwajalein). The Master Control Station (MCS) is located in Colorado Springs, Colorado. The monitor stations passively track all satellites in view, accumulating ranging data. This data is processed at the Master Control Station to determine satellite orbits and to update each satellite's Navigation message. Updated information is transmitted to each satellite via the Ground Antennas. New navigation and ephemeris information is calculated from the monitored data and can be uploaded to the satellites once or twice daily. This information is sent to the satellite via an S band link.

2.1.1 User Segment

Anyone with a GPS receiver is part of this segment. The list of users keeps growing. New applications are coming on line daily.

2.2 Calculating Positions

A GPS receiver determines its position by computing the position of four or more satellites within view and then measuring its range from each. By solving four simultaneous equations, with four unknowns, the receiver calculates its coordinates in an Earth Centered Earth Fixed (ECEF) coordinate system.

2.2.1 Generating GPS Signal Transit Time

Each satellite transmits its exact position and precise on-board clock time to Earth at a frequency of 1575.42 MHz. These signals are transmitted at the speed of light (300,000 km/s) and therefore require approx. 67.3 ms to reach a position on the Earth's surface located directly below the satellite. The signals require a further 3.33 us for each excess kilometer of travel. If you wish to establish your position on land (or at sea or in the air), all you require is an accurate clock. By comparing the arrival time of the satellite signal with the on board clock time the moment the signal was emitted, it is possible to determine the transit time of that signal. The distance S to the satellite can be determined by using the known transit time. Measuring signal transit time and knowing the distance to a satellite is still not enough to calculate one's own position in 3-D space. To achieve this, four independent transit time measurements are required. It is for this reason that signal communication with four different satellites is needed to calculate one's exact position and time. Why this should be so, can best be explained by initially determining one's position on a plane.

2.2.2 Determining a Position on a Plane

Imagine that you are wandering across a vast plateau and would like to know where you are. Two satellites are orbiting far above you transmitting their own on board clock times and positions. By using the signal transit time to both satellites you can draw two circles with the radii S1 and S2 around the satellites. Each radius corresponds to the distance calculated to the satellite. All possible distances to the satellite are located on the circumference of the circle. If the position above the satellites is excluded, the location of the receiver is at the exact point where the two circles intersect beneath the satellites (Figure 2.2), Two satellites are sufficient to determine a position on the X/Y plane.

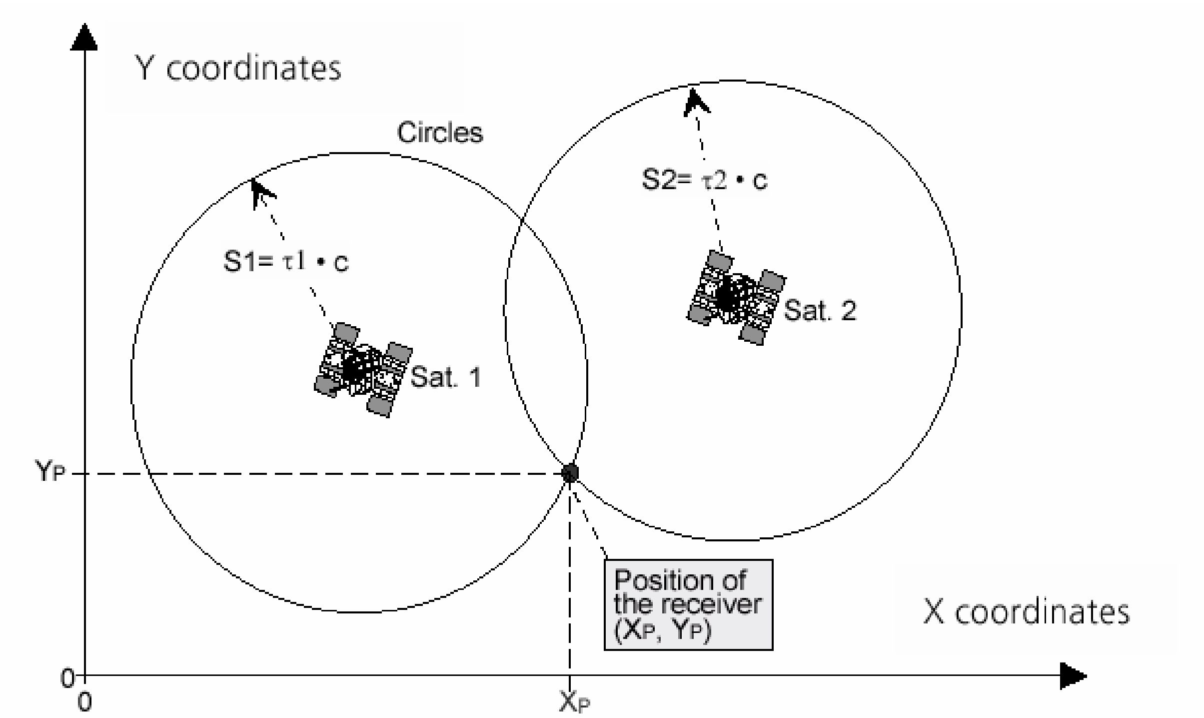

Figure 2.2: The position of the receiver at the intersection of the two circles

In reality, a position has to be determined in three-dimensional space, rather than on a plane. As the difference between a plane and three-dimensional space consists of an extra dimension (height Z), an additional third satellite must be available to determine the true position. If the distance to the three satellites is known, all possible positions are located on the surface of three spheres whose radii correspond to the distance calculated. The position sought is at the point where all three surfaces of the spheres intersect (Figure 2.4).

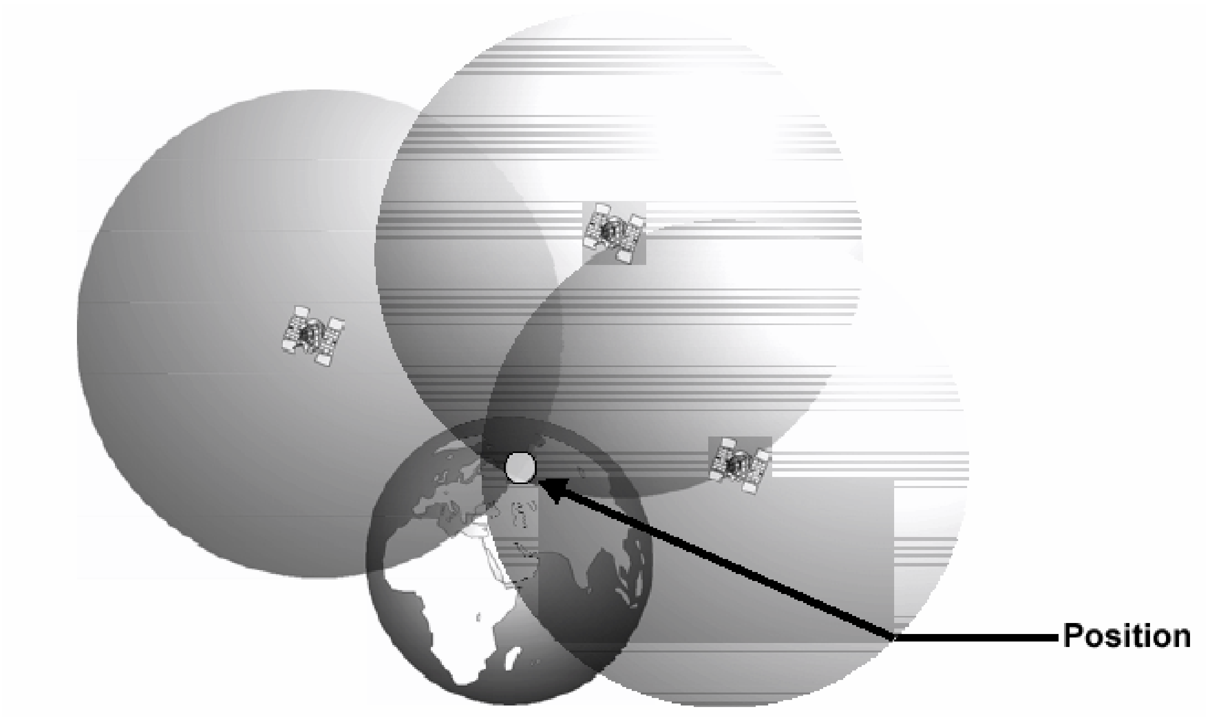

Figure 2.3: The position is determined at the point where all three spheres intersect

All statements made so far will only be valid, if the terrestrial clock and the atomic clocks on board the satellites are synchronized, i.e. signal transit time can be correctly determined.

2.2.3 The Effect and Correction of Time Error

We have been assuming up until now that it has been possible to measure signal transit time precisely. However, this is not the case. For the receiver to measure time precisely a highly accurate, synchronized clock is needed. If the transit time is out by just 1 μs this produces a positional error of 300m. As the clocks on board all three satellites are synchronized, the transit time in the case of all three measurements is inaccurate by the same amount. Mathematics is the only thing that can help us now. We are reminded when producing calculations that if N variables are unknown, we need N independent equations.

If the time measurement is accompanied by a constant unknown error, we will have four unknown variables in 3-D space:

- Longitude
- Latitude
- Height

- Time error

It therefore follows that in three-dimensional space four satellites are needed to determine a position. The GPS satellites are distributed around the globe in such a way that at least 4 of them are always “visible” from any point on Earth.

2.2.4 2D and 3D Navigation

3D (three dimensional) Navigation is a navigation mode in which altitude and horizontal position (longitude and latitude) are determined from satellite range measurements. It requires a minimum of four visible satellites. This is the standard navigation mode of GPS receivers.

2D (two dimensional) Navigation is a navigation mode in which a fixed altitude is used for one or more position calculations while horizontal (2D) position can vary freely based on satellite range measurements. It requires a minimum of three visible satellites. 2D navigation is typically used if only three satellites are visible because of obstructed view. The accuracy of 2D positions heavily depends on the accuracy estimation.

2.3 The GPS Navigation Message

The navigation message is a continuous stream of data transmitted at 50 bits per second. Each satellite relays the following information to Earth:

-System time and clock correction values
- Its own highly accurate orbital data (ephemeris)
- Approximate orbital data for all other satellites (almanac)
-System health, etc.

The navigation message is needed to calculate the current position of the satellites and to determine signal transit times. The data stream is modulated to the HF carrier wave of each individual satellite. Data is transmitted in logically grouped units known as frames or pages. Each frame is 1500 bits long and takes 30 seconds to transmit. The frames are divided into 5 subframes. Each subframe is 300 bits long and takes 6 seconds to transmit. In order to transmit a complete almanac, 25 different frames are required (called pages). Transmission time for the entire almanac is therefore 12.5 minutes.

2.3.1 Structure of the Navigation Message

A frame is 1500 bits long and takes 30 seconds to transmit. The 1500 bits are divided into five subframes each of 300 bits (duration of transmission 6 seconds). Each subframe is in turn divided into 10 words each containing 30 bits. Each subframe begins with a telemetry word and a handover word (HOW). A complete navigation message consists of 25 frames (pages). A frame is divided into five subframes, each subframe transmitting different information.

-Subframe 1 contains the time values of the transmitting satellite, including the parameters for correcting signal transit delay and on board clock time, as well as information on satellite health and an estimation of the positional accuracy of the satellite. Subframe 1 also transmits the so-called 10-bit week number (a range of values from 0 to 1023 can be represented by 10 bits). GPS time began on Sunday, 6th January 1980 at 00:00:00 hours. Every 1024 weeks the week number restarts at 0.

-Subframes 2 and 3 contain the ephemeris data of the transmitting satellite. This data provides extremely accurate information on the satellite's orbit.

-Subframe 4 contains the almanac data on satellite numbers 25 to 32 (N.B. each subframe can transmit data from one satellite only), the difference between GPS and UTC time and information regarding any measurement errors caused by the ionosphere.

-Subframe 5 contains the almanac data on satellite numbers 1 to 24 (N.B. each subframe can transmit data from one satellite only). All 25 pages are transmitted together with information on the health of satellite numbers 1 to 24.

2.3.1.1 Comparison between Ephemeris and Almanac Data

The satellite orbit information retrieved from an almanac is much less accurate than the information retrieved from the ephemeris. In order to achieve the typical GPS accuracy (see Table 2.1), a GPS receiver needs to download ephemeris data for all satellites it tracks.

Some GPS receivers (including the ANTARIS™ GPS Technology) are able to navigate based on almanac orbits while the ephemeris are not available (i.e. at startup period while the ephemeris are being downloaded). However, with an almanac only solution the position will have an accuracy of a few kilometers.

2.4 Accuracy of GPS

Although originally intended for purely military purposes, the GPS system is used today primarily for civil applications, such as surveying, navigation (air, sea and land), positioning, measuring velocit, determining time, monitoring stationary and moving objects, etc. The system operator guarantees the standard civilian user of the service that the following accuracy (Table 2.1) will be attained for 95% of the time (2drms value):

Table 2.1: Accuracy of the standard civilian service

Horizontal Accuracy	Vertical Accuracy	Time Accuracy
≤ 13m	≤ 22m	~40ns

2.4.1 Error Consideration and Satellite Signal

2.4.1.1 Error Consideration

Error components in calculations have so far not been taken into account. In the case of the GPS system, several causes may contribute to the overall error:

-Satellite clocks: although each satellite has four atomic clocks on board, a time error of just 10 ns creates an error in the order of 3 m.

-Satellite orbits: The position of a satellite is generally known only to within approx. 1 to 5 m.

-Speed of light: the signals from the satellite to the user travel at the speed of light. This slows down when traversing the ionosphere and troposphere and can therefore no longer be taken as a constant.

-Measuring signal transit time: The user can only determine the point in time at which an incoming satellite signal is received to within a period of approx. 10-20 ns, which corresponds to a positional error of 3-6 m. The error component is increased further still as a result of terrestrial reflection (multipath).

-Satellite geometry: The ability to determine a position deteriorates if the four satellites used to take measurements are close together. The effect of satellite geometry on accuracy of measurement (see 2.5.1.2) is referred to as GDOP (Geometric Dilution Of Precision).

The errors are caused by various factors that are detailed in Table 2.2, which includes information on horizontal errors. Sigma-1 (68.3%) and sigma-2 (95.5%) are also given. Accuracy is, for the most part, better than specified, the values applying to an average satellite constellation (DOP value).

Table 2.2: Cause of errors

Cause Of Error	**Error**
Effects of the ionosphere	4 m
Satellite clocks	2.1 m
Receiver measurements	0.5 m
Ephemeris data	2.1 m
Effects of the troposphere	0.7 m
Multipath	1.4 m
Total RMS value (unfiltered)	5.3 m
Total RMS value (filtered)	5.1 m
Vertical error (sigma-1 (68.3%) VDOP=2.5)	12.8m
Vertical error (sigma-2 (95.5.3%) VDOP=2.5)	25.6m
Horizontal error (sigma-1 (68.3%) HDOP=2.0)	10.2m
Horizontal error (sigma-2 (95.5%) HDOP=2.0)	20.4m

Note: Measurements undertaken by the US Federal Aviation Administration over a long period of time indicate that in the case of 95% of all measurements, horizontal error is less than 7.4 m and vertical error is less than 9.0 m. In all cases, measurements were conducted over a period of 24 hours.

In many instances, the number of error sources can be eliminated or reduced (typically to 1...2 m, sigma-2) by taking appropriate measures (Differential GPS, DGPS).

2.4.1.2 DOP (Dilution of Precision)

The accuracy with which a position can be determined using GPS in navigation mode depends, on the one hand, on the accuracy of the individual pseudo-range measurements, and on the other, on the geometrical configuration of the satellites used. This is expressed in a scalar quantity, which in navigation literature is termed DOP (Dilution of Precision).

There are several DOP designations in current use:

- GDOP: Geometrical DOP (position in 3-D space, incl. time deviation in the solution)
-PDOP: Positional DOP (position in 3-D space)
-HDOP: Horizontal DOP (position on a plane)
-VDOP: Vertical DOP (height only)

The accuracy of any measurement is proportionately dependent on the DOP value. This means that if the DOP value doubles, the error in determining a position increases by a factor of two.

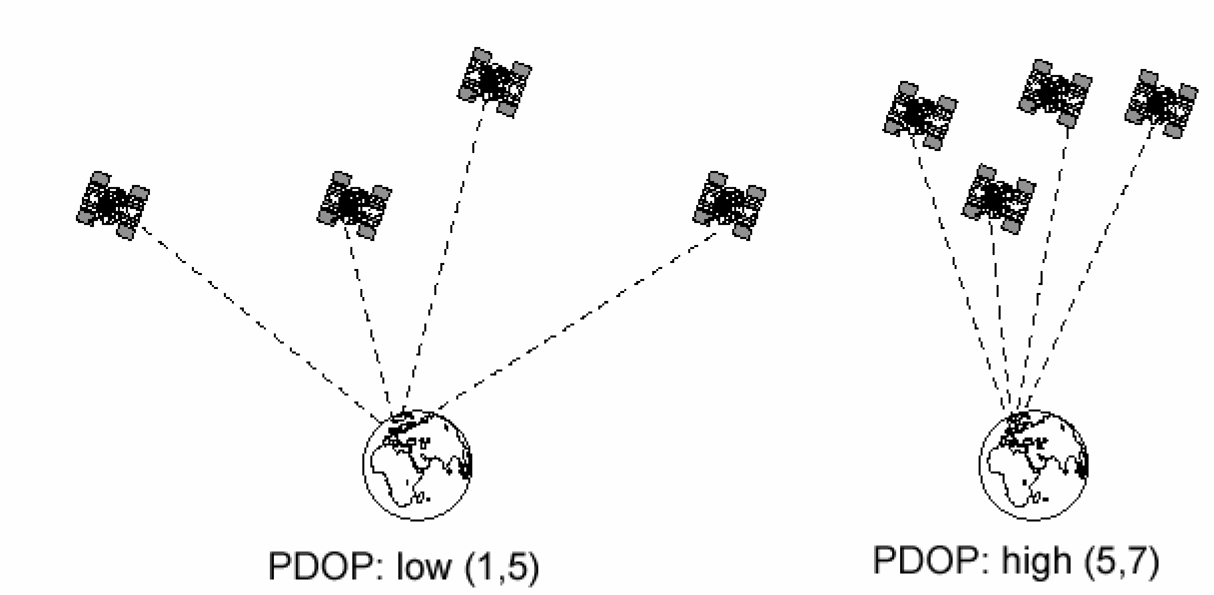

Figure 2.4 Satellite geometry and PDOP

PDOP can be interpreted as a reciprocal value of the volume of a tetrahedron, formed by the positions of the satellites and user, as shown in Figure 2.4. The best geometrical situation occurs when the volume is at a maximum and PDOP at a minimum.

PDOP played an important part in the planning of measurement projects during the early years of GPS, as the limited deployment of satellites frequently produced phases when satellite constellations were geometrically very unfavorable. Satellite deployment today is so good that PDOP and GDOP values rarely exceed 3.

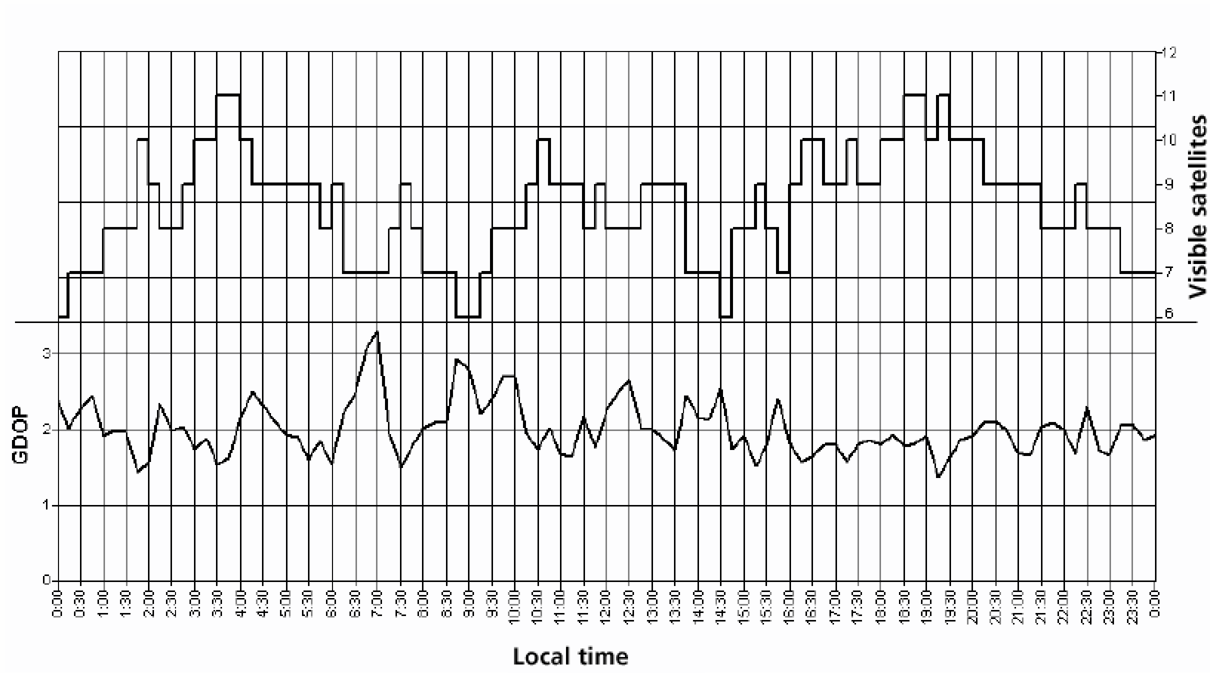

Figure 2.5 GDOP values and the number of satellites expressed as a time function

It is therefore unnecessary to plan measurements based on PDOP values, or to evaluate the degree of accuracy attainable as a result, particularly as different PDOP values can arise over the course of a few minutes. In the case of kinematic applications and rapid recording processes, unfavorable geometrical situations that are short lived in nature can occur in isolated cases. The relevant PDOP values should therefore be included as evaluation criteria when assessing critical results. PDOP values can be shown with all planning and evaluation programmes supplied by leading equipment manufacturers (Figure 2.6).

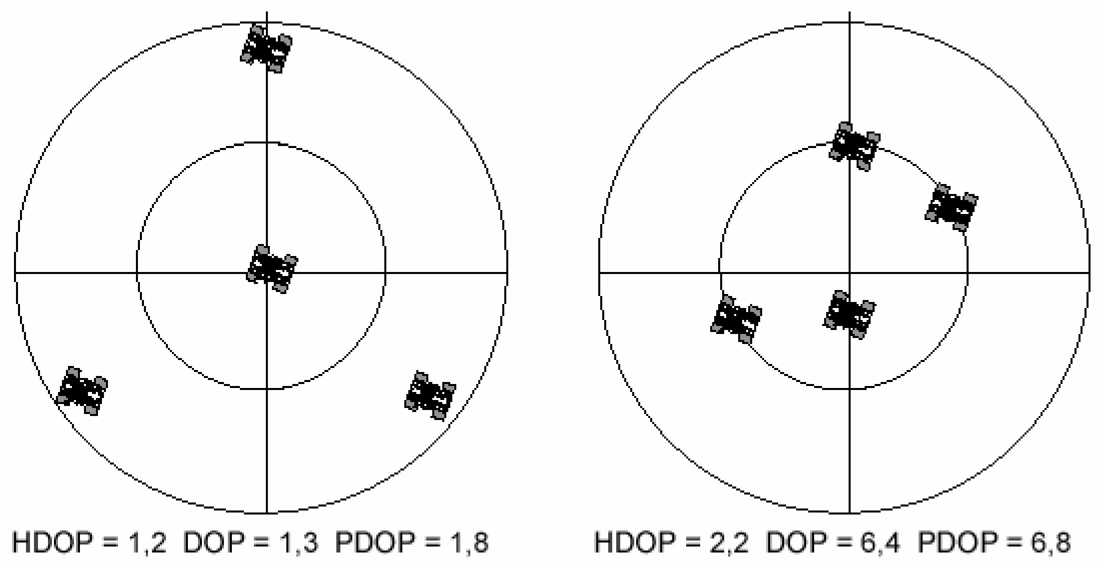

Figure 2.6: Effect of satellite constellations on the DOP value

2.4.1.3 Multipath

A multi-path environment exists if GPS signals arrive at the antenna directly from the satellite, (line of sight, LOS) and also from reflective surfaces, e.g. water or building walls. If there is a direct path in addition to the reflected path available, the receiver can usually detect the situation and compensate to some extend. If there is no direct line of sight, but only reflections, the receiver is not able to detect the situation. Under these multipath conditions the range measurement to the satellite will provide incorrect information to the navigation solution, resulting in less accurate position. If there are only few satellites in sight, the navigation solution might be wrong by several 100 m.

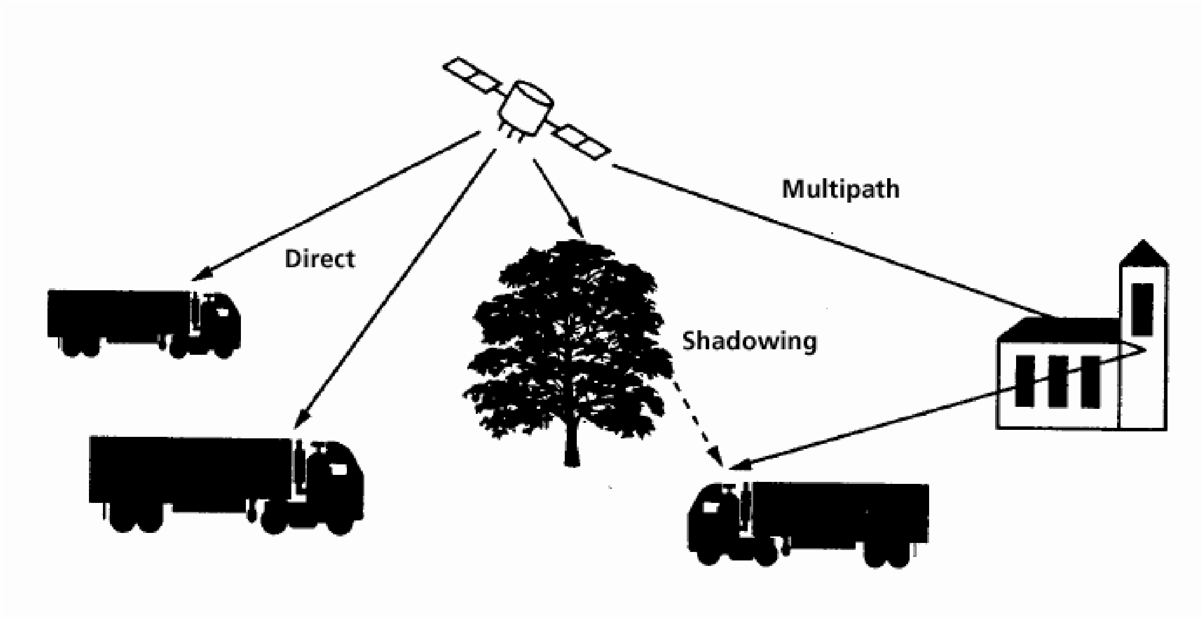

Figure 2.7: A multipath environment

If there is a LOS available, the effect of multi-path is actually twofold. First, the correlation peak will be distorted which results in a less precise position. This effect can be compensated for by advanced receiver technology as our patented multipath mitigation scheme. The second relates to the carrier phase relation of the direct and reflected signal, the received signal strength is subject to an interference effect. The two signals may cancel out each other (out of phase) or add onto each other (in phase). Even if the receiver remains stationary, the motion of the satellite will change the phase relation between direct and reflected signal, resulting in a periodic modulation of the C/N0 measured by the receiver. The receiver cannot compensate for the second effect, because the signals cancel out at the antenna, not inside the GPS unit. However, as the reflected signal is usually much weaker than the direct signal, the two signals will not cancel out completely. The reflected signal will also have an inverted polarity (left hand circular rather than right hand circular), further reducing the signal level, particularly if the antenna has good polarization selectivity. Water is a very good reflector; so all seaborne applications require special attention to reflected signals arriving at the antenna from the underside, i.e. the water surface. Also, location of the antenna close to vertical metal surfaces can be very harmful since metal is an almost perfect reflector. When mounting an antenna on top of a reflective surface, the antenna should be mounted as close to the surface as possible. Then, the reflective surface will act as an extension of the antennas ground plane and not as a source of multi-path. Because the periodicity of the modulation of C/N0 is easily visible in severe multi-path environments, the user can detect the multi-path situation by observing the C/No values for a period of time.

2.5 Differential-GPS (DGPS)

A horizontal accuracy of approx. 20 m is probably not sufficient for every situation. In order to determine the movement of concrete dams down to the nearest millimeter, for example, a greater degree of accuracy is required. In principle, a reference receiver is always used in addition to the user receiver. This is located at an accurately measured reference point (i.e. the coordinates are known). By continually comparing the user receiver with the reference receiver, many errors (even SA ones, if it is switched on) can be eliminated. This is because a difference in measurement arises, which is known as Differential GPS (DGPS). A reference station whose coordinates are precisely known measures signal transit time to all visible GPS satellites and determines the pseudo-range from this variable (actual value). Because the position of the reference station is known precisely, it is possible to calculate the true distance (target value) to each GPS satellite. The difference between the true value and the measured pseudo-range can be ascertained by simple subtraction and will give the correction value (difference between the actual and target value). The correction value is different for every GPS satellite and will hold good for every GPS user within a radius of a few hundred kilometers. As the correction values can be used within a wide area to correct measured pseudo-range, they are relayed without delay via a suitable medium (transmitter, telephone, radio, etc.) to other GPS users. After receiving the correction values, a GPS user can determine a more accurate distance using the pseudo- range he has measured. All causes of error can therefore be eliminated with the exception of those emanating from receiver noise and multipath (see section 2.4.1.3). DGPS lost significance when the Selective Availability (SA) was discontinued in May 2000. These days, the applications of DGPS are typically limited to surveying[47].

3. ELECTRONICS CIRCUIT DESIGN FOR GPS RECEIVER

In the first part of this work real positioning data is used. And since the commercial off the shelf GPS receivers are expensive, A cheap GPS receiver with least necessary components is made. The uBlox brand GPS module with 1Hz sampling frequency, is used.

3.1 Features of the GPS Receiver

The GPS receiver consists of the following blocks.

- Power Block
- Antenna Block
- GPS module Block
- Communication Block

The Power Block converts 240Vac input signal to 5Vdc, which is needed by the uBlox MS1E module, MAX232 RS-232 driver/Receiver IC and MAX3232 3.0V to 5.0V level shifter IC.

The Antenna Block consists of an Active Antenna which connects directly to the MS1E, via a SMA connector.

GPS module Block consists of uBlox MS1E GPS receiver module placed on a Printed Circuit Board, which is designed for the proper configuration of the module.

The Communication Block consists of MAX 232 RS-232 driver/receiver IC, MAX 3232 3V to 5V level shifter IC and RS 232 cable.

In order to receive good GPS signals, the active antenna should be placed outdoor. The RS-232 cable is connected to any comm port of the PC and GPS receiver. Since the RS232 logic levels of the PC comm port(logic 1, -12V, logic0 +12V) and the MS1E(logic 1, +3V, logic0 -3V) are different, 3V to 5V level shifter IC MAX3232 and RS-232 driver/receiver IC MAX232 are used. The NMEA data can be read using any Comm Port Terminal software, like HyperTerminal. The receiver schematics, and internal and external views of the receiver are shown below.

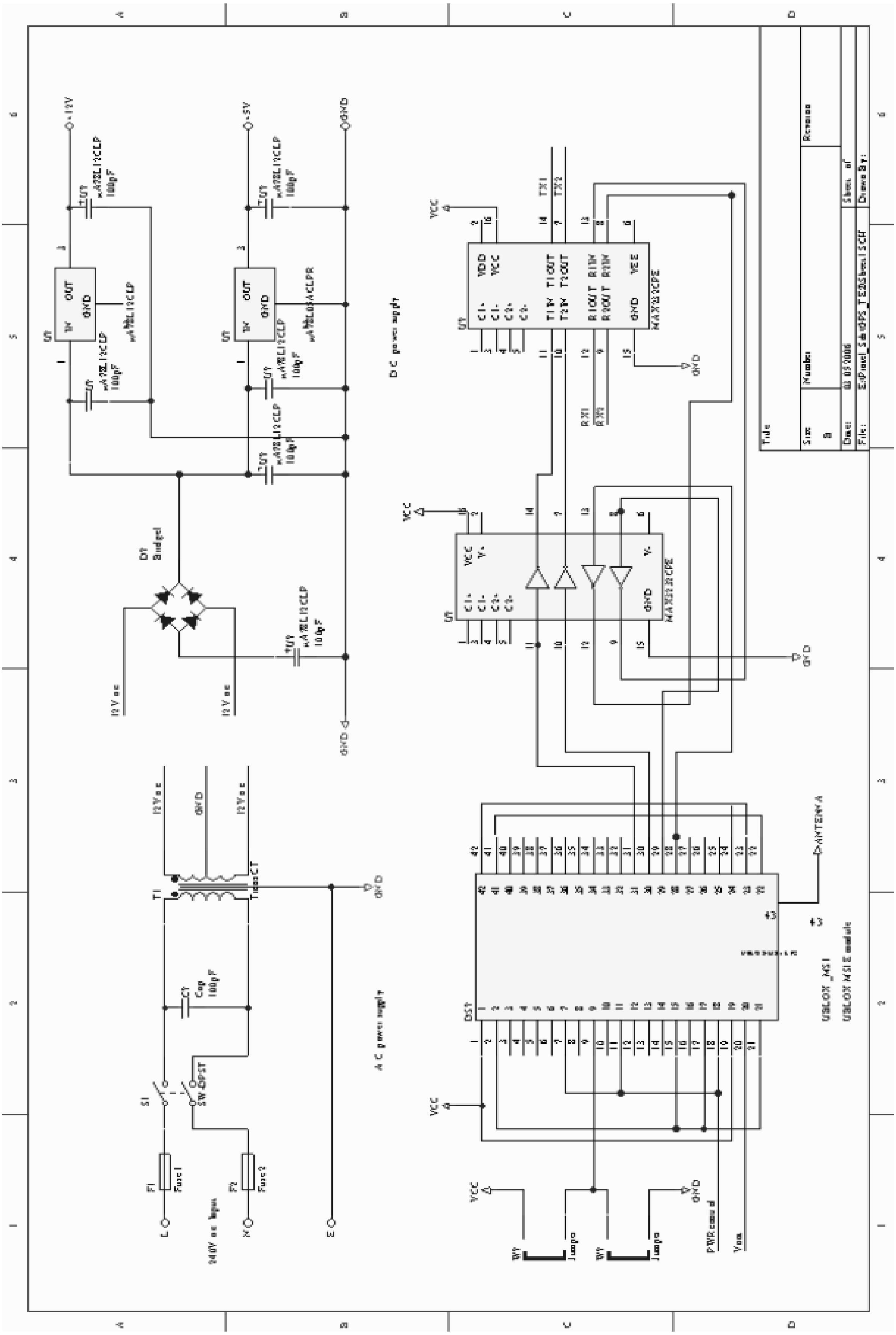

Figure 3.1: The GPS receiver schematics including all blocks

The circuit was drawn using PROTEL CAD software. And shematic view is as above.

Figure 3.2: External View of GPS receiver

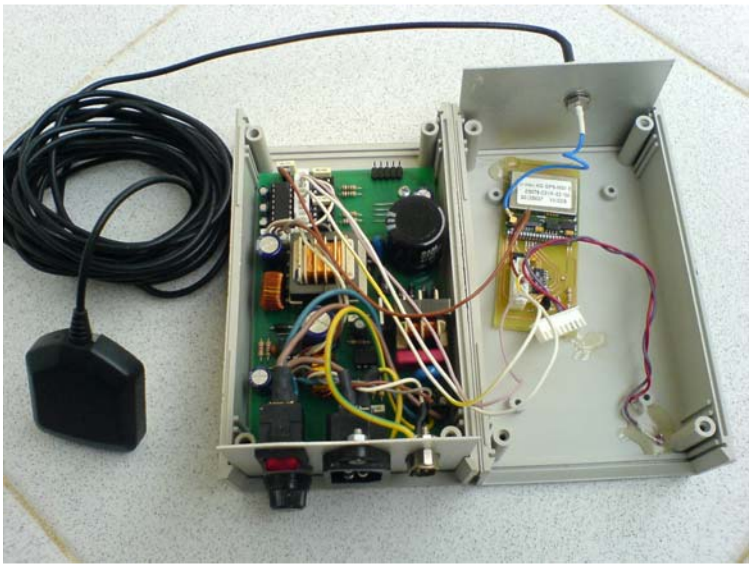

Figure 3.3: Internal View of GPS receiver

The GPS Receiver and the computer software communicated via a standard protocol called NMEA. Which includes the necessary data (receiver latitude, longitude, height, satellite positions vs..) The NMEA data is ASCII and communicates via RS232 port of computers, and looks like;

```
$GPGGA,134522.552,4056.8260,N,02728.9370,E,1,04,2.7,48.8,M,,,,0000*32
$GPGLL,4056.8260,N,02728.9370,E,134522.552,A*3C
$GPGSA,A,3,07,24,04,26,,,,,,,,,5.4,2.7,4.6*35
$GPGSV,3,1,11,30,75,001,,16,43,303,,06,42,254,,07,41,053,40*78
$GPGSV,3,2,11,26,27,191,38,04,21,108,42,24,16,063,45,09,16,163,*7C
$GPGSV,3,3,11,23,15,238,,01,14,295,,21,14,183,*43
$GPRMC,134522.552,A,4056.8260,N,02728.9370,E,0.05,333.78,150905,,*0A
$GPVTG,333.78,T,,M,0.05,N,0.1,K*68
$GPGGA,134523.552,4056.8260,N,02728.9370,E,1,04,2.7,48.8,M,,,,0000*33
$GPGLL,4056.8260,N,02728.9370,E,134523.552,A*3D
$GPGSA,A,3,07,24,04,26,,,,,,,,,5.4,2.7,4.6*35
$GPGSV,3,1,11,30,75,001,,16,43,303,,06,42,254,,07,41,053,40*78
$GPGSV,3,2,11,26,27,191,38,04,21,108,42,24,16,063,45,09,16,163,*7C
$GPGSV,3,3,11,23,15,238,,01,14,295,,21,14,183,*43
$GPRMC,134523.552,A,4056.8260,N,02728.9370,E,0.03,310.72,150905,,*06
$GPVTG,310.72,T,,M,0.03,N,0.1,K*65
```

The NMEA protocol is described in full detail in [47].

4. KALMAN FILTER

4.1 Linear Discrete Kalman Filter

Kalman Filter is developed by R. Kalman in year 1959 and is used for state estimation. At first it was considered as a topic of the Modern Control Theory, but later on it was considered as one of the most fundamental estimation technique. The mean-square estimation approach of random parameters is the foundation of Kalman Filter. Kalman Filter is widely used in modern-time applications: it is used in estimation of trajectory of spacecrafts, weapon launching systems, aircrafts, and ships, as well as oil searching, power systems, and even at agricultural crop yield estimate[34]. The optimality criterion of Kalman Filter comes from the criterion of minimizing the state variable error standard deviation[35].

4.2 Principles of Kalman Filter

Kalman Filter is widely used in the processing of navigation problems. This filter is used in such ways[4]:

1) Minimizing the measurement errors and obtaining more accurate measurement values.
2) Mixing various information sources.
3) Obtaining non-measurable state variables of a plane.
4) Diagnosis of noises in an airvehicle.

Let us consider the discrete linear dynamical system. State equation states the dynamics of the system, and observation equation states the measurement mechanism. These equations are written as below for the linear system;

State equation,

$$x(k+1) = \phi(k+1,k)x(k) + G(k+1,k)w(k) \tag{4.1}$$

Observation equation,

$$z(k) = H(k)x(k) + v(k) \tag{4.2}$$

Here $x(k)$ is the *n* dimensional system state vector. $\phi(k+1,k)$ is its *nxn* dimensional transfer matrix, $w(k)$ is the *r* dimensional zero-mean Gauss noise vector(process noise), with correlation matrix $E[w(k)wT(j)]Q(k)\delta(kj)$, E is stochastic mean operator, $\delta(kj)$ is the Kroenecker delta symbol.

$$\delta(kj) = \begin{cases} 1, k = j \\ 0, k \neq j \end{cases} \tag{4.3}$$

$G(k+1,k)$ is *nxr* dimensional transfer matrix of system noise, $z(k)$ is *s* dimensional observation vector, $H(k)$ is *sxn* dimensional observation matrix, $v(k)$ is *s* dimensional noise vector of the measurements with zero-mean Gauss noise, and correlation matrix $E[w(k)vT(j)] = 0, Vk, j$.

There is no correlation between process noise $w(k)$ and measurement noise $v(k)$.

When desired to estimate the state vector due to the $z(k)$ observation vector sequences, the linear filter method based on Kalman Filter approach should be used.

The optimal evaluation algorithm of the linear discrete system state vector is expressed with the following equations:

Estimate Equation:

$$\hat{x}(k/k) = \phi(k,k-1)\hat{x}(k-1/k-1) + K(k)[z(k) - H(k)\phi(k,k-1)\hat{x}(k-1/k-1)]$$
$$\hat{x}(k/k) = \hat{x}(k/k-1) + K(k)\tilde{z}(k/k-1)$$

(4.4)

Here *K(k)* is the Kalman Filter gain;

$$K(k) = P(k/k)H^T(k)R^{-1}(k)$$
$$K(k) = P(k/k-1)H^T(k)[H(k)P(k/k-1)H^T(k) + R(k)]^{-1}$$

(4.5)

Correletaion matrix of Kalman Filter estimate error is;

$$P(k/k) = P(k/k-1) - P(k/k-1)H^T(k)[H(k)P(k/k-1)H^T + R(k)]^{-1}H(k)P(k/k-1)$$

(4.6)

Correlation matrix of extrapolation error;

$$P(k/k-1) = \phi(k,k-1)P(k-1/k-1)\phi^T(k,k-1)Q(k-1)G^T(k,k-1) \tag{4.7}$$

Initial conditions;

$$\hat{x}(0/0) = \overline{x(0)}$$
$$P(0/0) = P(0)$$

The optimal filter algorithm stated in equations (4.4)-(4.7) is called the Kalman Filter;

The following equivalent equations are valid for $K(k)$ and $P(k/k)$;

$$\begin{aligned} K(k) &= P(k/k)H^T(k)R^{-1}(k) \\ P(k/k) &= (I - K(k)H(k))P(k/k-1) \\ P(k/k) &= [P^{-1}(k/k-1) + H^T(k)R^{-1}(k)H(k)P(k/k-1)]^{-1} \\ P(k/k) &= P^{-1}(k/k-1)[I + H^T(k)R^{-1}(k)H(k)P(k/k-1)]^{-1} \end{aligned} \qquad \textbf{(4.8)}$$

Here *I* is unity matrix.

$$\Delta(k) = z(k) - H(k)\hat{x}(k/k-1) \qquad \textbf{(4.9)}$$

Expression (4.9) is called as innovation process, and reorganizing equation (4.4) we obtain;

$$\hat{x}(k/k) = \hat{x}(k/k-1) + K(k)\Delta(k) \qquad \textbf{(4.10)}$$

x(0) and *P(0)* initial conditions known prior, correlation matrix of process noise *Q(k)* and correlation matrix of observation error *R(k)* are necessary beforehand, in order the kalman filter work.

The Kalman Filter structural schematics is shown in Fig.(4.1)

According to formula (4.4) the estimation is the sum of $\hat{x}(k/k-1)$ extrapolation value and the $K(k)\tilde{z}(k/k-1)$ correction difference. Extrapolation value is obtained by multiplication of the value at previous step by the system transfer matrix. And then, the extrapolated value is give an innovation. Namely, The Kalman Filter works on the principle of innovating the estimated value.

The process of the evolution of the Kalman Filter estimate in time is demonstrated in figure (4.2). Typical Kalman Filter cycle involves the following processes:

1) Estimation of the value one step further(finding of the extrapolation value) $\hat{x}(k/k-1)$

2) Multiplication of $\hat{x}(k/k-1)$ by $H(k)$ from left, the estimation of measurement.

3) Finding the difference between the measurement and the extrapolation value (the innovation process) $\tilde{z}(k/k-1) = z(k) - H(k)\hat{x}(k/k-1)$

4) Multiplication of $\tilde{z}(k/k-1)$ from left by *K(k)* and summation with $\hat{x}(k/k-1)$, thus obtaining $\hat{x}(k/k)$

5) Storage of $\hat{x}(k/k)$ estimation for the next cycle and repeating the process.

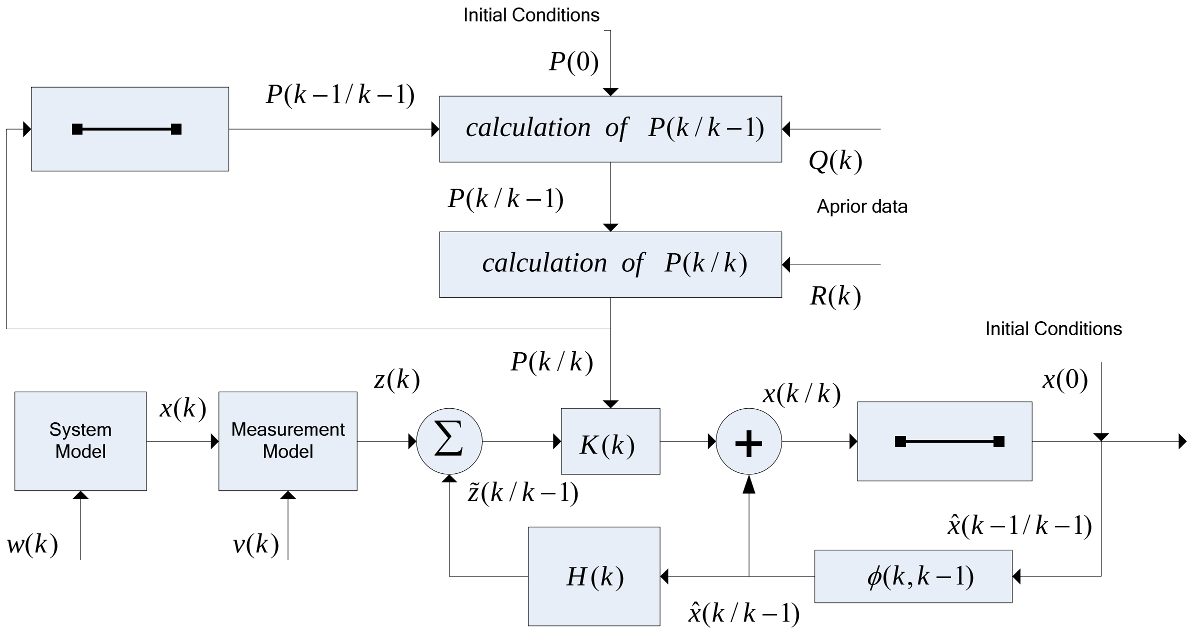

Figure 4.1: Kalman Filter structural schematics[33].

Important features of the Kalman Filter are given below as;

1) The estimate obtained by the Kalman Filter is more linear compared to the measurement value.

2) For the reason of this filter being linear, the correlation matrix *P(k/k)* of estimate error is not coupled with the measurement *z(k),* and can be calculated beforehand.

3) When the mathematical model of the dynamical system is clearly stated, the filter algorithm can easily be performed by the help of a computer(since it is also a discrete device).

4) For stagnant dynamical systems at stability, the Kalman Filter corresponds with the Wiener filter.

5) The filtering algorithms can easily be deployed for multidimensional states.

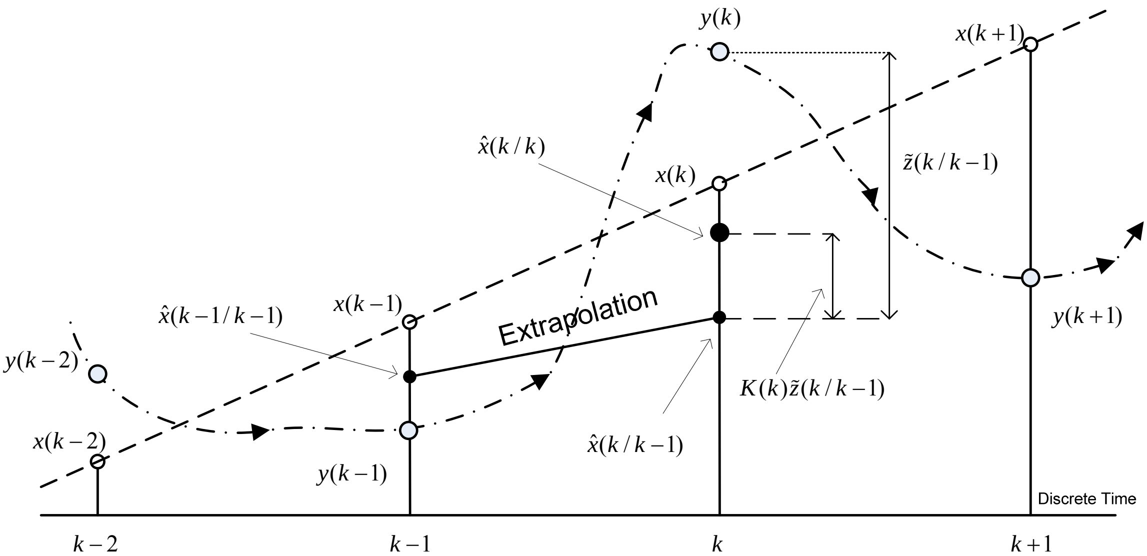

Figure 4.2: Time diagram demonstrating the mechanism of Kalman process.

When the mathematical model of the system is not known or is changing during process time, filters of adaptive behaviour are used. This adaptive process is united of the identification of parameters or(and) system model identification.

When the equations are nonlinear, they need to be linearised to some degree before implementing the Kalman Filter.

5. KALMAN FILTER BASED IMPROVEMENT OF GPS POSITION DATA USING SATELLITE DISTANCES METHOD

Today Satellite Navigation Systems are widely used to determine position and velocity of an object at a certain time. The Satellite System widely used is named NAVSTAR, and are controlled by the US Department of Defense. The satellites are configured to transmit two kinds of codes the, C/A code, which is available free for civilian use and the P code which needs special decoding circuitry in order to be serviceable. The US DoD has configured the C/A code so that receiver obtains a certain position error, which varies up to 100m. This functioning of the GPS systems is called Selective Availability(SA). There are some methods that civilian users who want more accurate positioning can apply, one of them is using Linear Kalman Filtering techniques.

5.1 Satellite Distances Method

In order to obtain horizontal positioning only, 3 satellites in view will be enough, for vertical positioning along with horizontal, we need at least 4 satellites.

We have used real GPS data in this study, and Linear Kalman Filter, to improve the position.

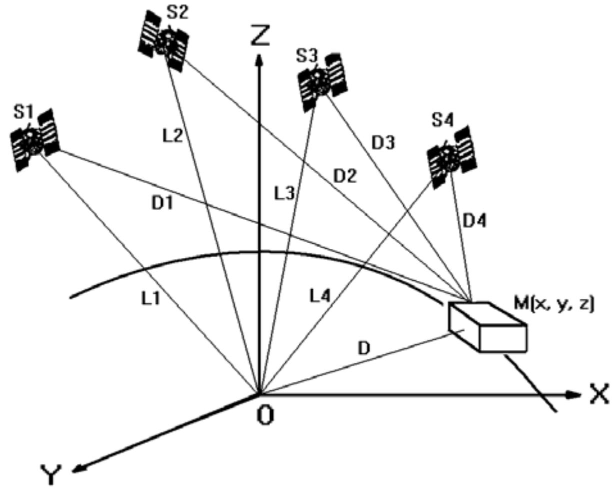

Figure 5.1: Locating the object using satellite distances

We denote the number of satellites viewed by n, the cartesian coordinates of the object viewed as x,y,z, the cartesian coordinates of satellites viewed as x_i ,y_i ,z_i $(i=\overline{1,n})$, the distances from satellites to the cartesian origin of axis as L_i $(i=\overline{1,n})$, distances from satellites to object as D_i $(i=\overline{1,n})$.

The distance of object from origin :

$$D^2=x^2+y^2+z^2, \quad \textbf{(5.1)}$$

The distances of satellites in view, from origin :

$$L_i^2=x_i^2+y_i^2+z_i^2 , \quad i=\overline{1,n} \quad \textbf{(5.2)}$$

The distances of object from satellites in view can be obtained as :

$$D_i=((x_i-x)^2+(y_i-y)^2+(z_i-z)^2)^{1/2}+b , \quad i=\overline{1,n} \quad \textbf{(5.3)}$$

In this equation x_i ,y_i ,z_i are the descartes coordinates of the satellites, n is the number of satellites in view , x,y,z are the descartes coordinates of the object, b is the clock bias between the transmit of the signal from the satellite to the object.

Let us denote the distance measuring eq (5.3) as :

$$(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2 = (D_i - b - w_i)^2 \quad \textbf{(5.4)}$$

After performing necessary transformations in the equation (5.4), regarding statements (1) and (2), the following equation is obtained

$$D_i^2 + b^2 - 2D_i b = L_i^2 + D^2 - 2(x_i x + y_i y + z_i z) . \quad \textbf{(5.5)}$$

We put $i=1,..,4$ values in statement (5.5) respectively and subtract the resulting equations from the sides as in the following order : subtract (5.2) from (5.1); subtract (5.3) from (5.1); subtract (5.4) form (5.1). As a result of necessary mathematical transformations the following equation system is obtained:

$$(x_1 - x_2)x + (y_1 - y_2)y + (z_1 - z_2)z + (D_2 - D_1)b = \frac{1}{2}(L_1^2 - L_2^2 + D_2^2 - D_1^2)$$
$$(x_1 - x_3)x + (y_1 - y_3)y + (z_1 - z_3)z + (D_3 - D_1)b = \frac{1}{2}(L_1^2 - L_3^2 + D_3^2 - D_1^2)$$
$$(x_1 - x_4)x + (y_1 - y_4)y + (z_1 - z_4)z + (D_4 - D_1)b = \frac{1}{2}(L_1^2 - L_4^2 + D_4^2 - D_1^2)$$

(5.6)

If eq(5.6) is organized in matrix form :

$$A = \begin{bmatrix} x_1 - x_2 & y_1 - y_2 & z_1 - z_2 & D_2 - D_1 \\ x_1 - x_3 & y_1 - y_3 & z_1 - z_3 & D_3 - D_1 \\ x_1 - x_4 & y_1 - y_4 & z_1 - z_4 & D_4 - D_1 \end{bmatrix}$$

$$X^T = [x, y, z, b] \qquad \textbf{(5.7)}$$

$$Z = \begin{bmatrix} \frac{1}{2}(L_1^2 - L_2^2 + D_2^2 - D_1^2) \\ \frac{1}{2}(L_1^2 - L_3^2 + D_3^2 - D_1^2) \\ \frac{1}{2}(L_1^2 - L_4^2 + D_4^2 - D_1^2) \end{bmatrix}$$

Above statements (5.7) and equation system (5.6) can be expressed in matrix from as:

$$Z = AX + Y \qquad \textbf{(5.8)}$$

In statistics this model is called as linear regression, where X is the unknown (which must be estimated) vector, Z is the measurement vector, A is the regression matrix; V is the error vector.

5.2 The Kalman Filter For the Improvement of GPS Measurement Data

When Kalman Filter of the form (5.4) is applied to model in (5.8) the following eqs are obtained :

$$\hat{X}(k) = \hat{X}(k-1) + K(k)\left[Z(k) - A(k)\hat{X}(k-1)\right] \qquad \textbf{(5.9)}$$

$$K(k) = P(k-1)A^T(k)\left[A(k)P(k-1)A^T(k) + R(k)\right]^{-1} \quad \textbf{(5.10)}$$

$$P(k) = P(k-1) - P(k-1)A^T(k) \times \left[A(k)P(k-1)A^T(k) + R(k)\right]^{-1} A(k)P(k-1) \quad \textbf{(5.11)}$$

Here *K(k)* is the gain matrix, *P(k)* is a covariance matrix of estimate errors. The Kalman filter obtained in eqs (5.9), (5.10), (5.11) is recursive and has the ability of estimating the parameters of the model (5.8).

5.4 Experimental Results

We used Kalman Software to implement the real GPS data into the Linear Kalman Filter, the GPS receiver gives the data in NMEA protocol format. The receiver delivers 1 sample per second. The receiver gives the position of object, and the satellites in view in geodetic format. In order to obtain linear position data, which is easier to apply to Linear Kalman Filter. The satellite position given by the receiver consists of elevation and azimuth of the satellite.

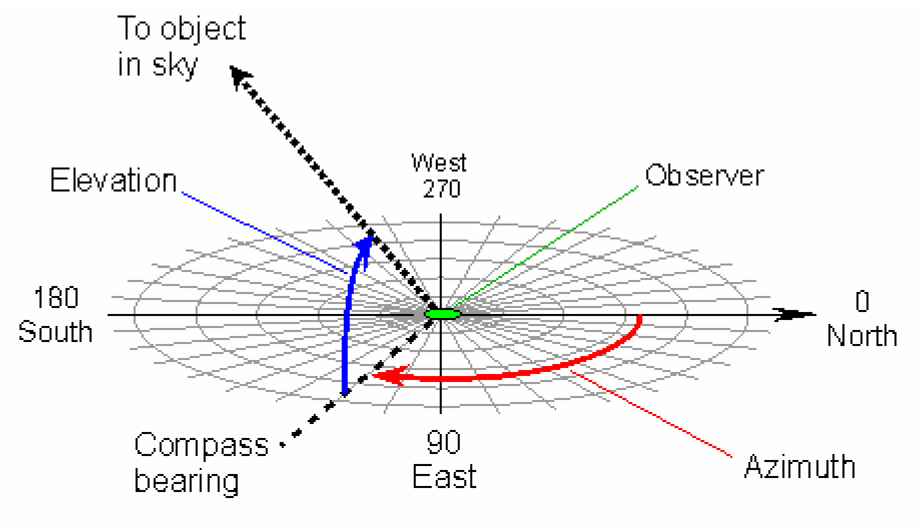

Figure 5.2: illustration of elevation and azimuth data of a GPS satellite

The conversion of Geodetic coordinates to Descartes coordinates are descibed in Appendix.

The actual position of the object is obtained after taking the mean of 1000 samples at a fixed position. In order to shorten up the MATLAB process time, I saved the

NMEA output to text files and after calculation of the descartes coordinates of the satellite and object positions, the results are saved in MATLAB .MAT file format.

The results for 4,5,6 and 7 satellites are introduced into the Kalman Filter, then all the results(4,5,6,7 satellite) are combined to obtain a realistic observation environment. The rest of the results are shown in the APPENDIX.

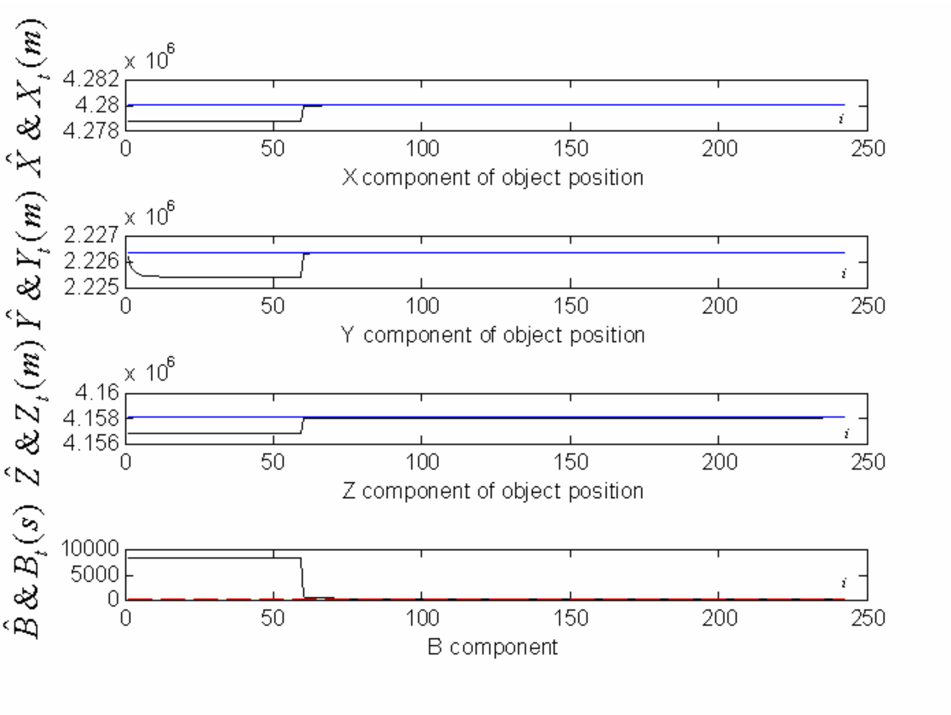

Figure 5.3: X, Y, Z and B true values and Kalman Filter estimates

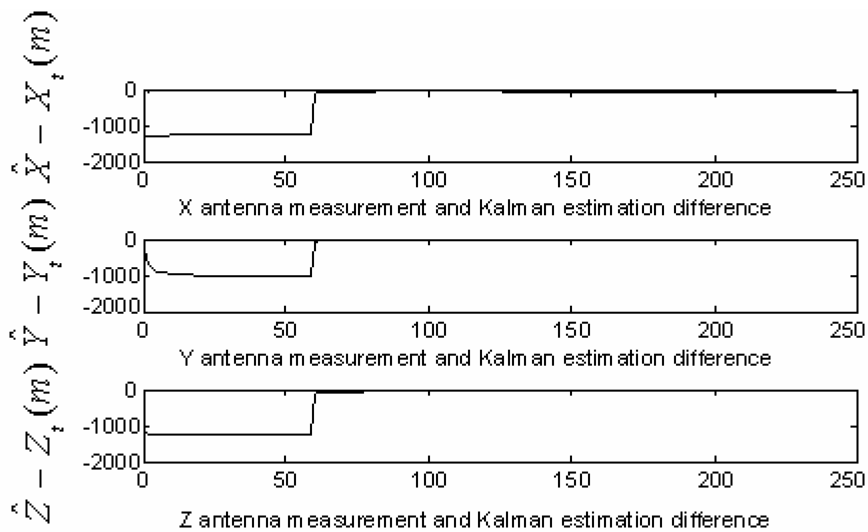

Figure 5.4: Differences between true positions and KF position estimates when 4 satellites in view

Table 5.1: Errors between GPS antenna true position and Kalman Filter estimates when 4 satellites available

Measurement and Estimation Step	X Error Between Antenna Measurement and KF Estimation(m)	Y Error Between Antenna Measurement and KF Estimation(m)	Z Error Between Antenna Measurement and KF Estimation(m)	B Error Between Antenna Measurement and KF Estimation(m)
25	-1269,841228	-1013,074753	-1253,132272	8179,713509
50	-1268,960912	-1029,418904	-1253,682613	8177,68152
75	-49,44285928	-26,04021321	-47,27271735	311,443038
100	-39,03458884	-20,11396438	-36,75110531	241,639933
125	-33,9530401	-17,51551039	-31,64475325	207,6207473
150	-31,44829021	-16,5138203	-29,39043771	191,0214466
175	-30,56250737	-16,29183121	-28,26810379	183,7965579
200	-29,88738491	-16,0473993	-27,60171214	178,9570348
225	-25,55071167	-13,89752041	-24,16095077	155,0446965
243	-21,49465459	-11,52991577	-20,4289251	131,1651358

6. AIR DATA SYSTEM

Air data systems provide information on quantities such as, pressure altitude, vertical speed, calibrated airspeed, true airspeed, Mach number, static air temperature and air density ratio. This information is essential for the pilot to fly the aircraft safely and is also required by a number of key avionic subsytems which enable the pilot to carry out the mission. It is thus one of the key avionic systems in its own right and forms part of the essential core of avionic sub systems required all modern aircraft, civil or military. In this section a short desrciption of the ADS is given.

6.1 Air Data Measurements

Air data quantities pressure altitude, vertical speed, calibrated airspeed, true airspeed, true, Mach number etc. are derived from three basic measurements by sensors connected to probes which measure:

- Total (or Pitot) pressure
- Static pressure
- Total (or indicated) air temperature

The total pressure P_T is measured by means of an absolute pressure sensor (or transducer) connected to pitot tube facing the moving airstream. This measures the impact pressure Q_C that is the pressure exerted to bring the moving airstream to rest relative to the Pitot tube plus the static pressure P_S of the free airstream ie $P_T = Q_C + P_S$.

The static pressure of the free airstream P_S is measured by an absolute pressure transducer connected to a suitable orifice located where the surface pressure is nearly the same as the pressure of the surrounding atmosphere.

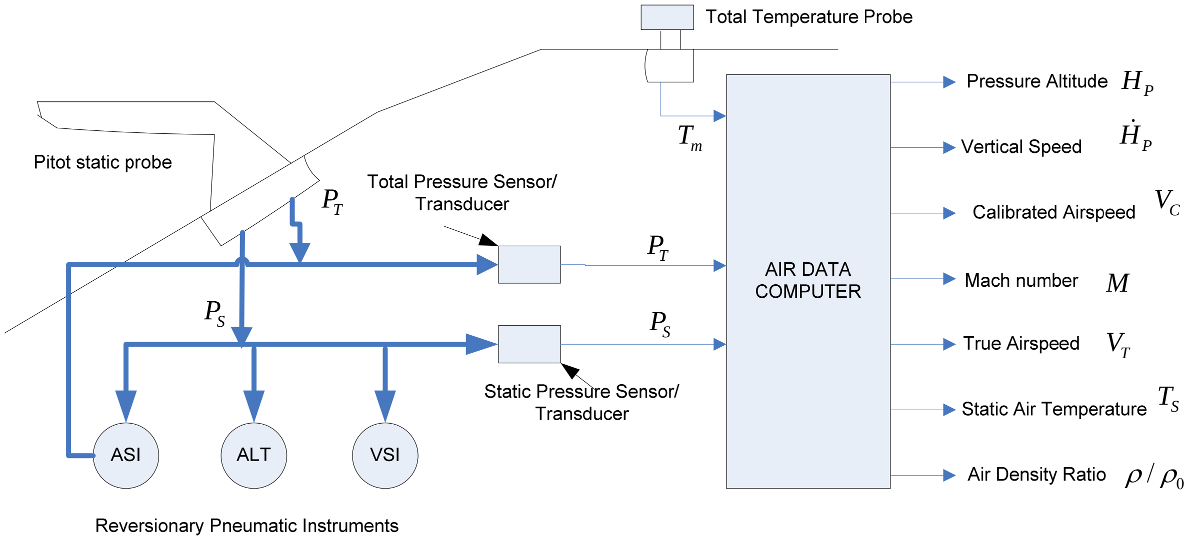

Figure 6.1: Basic Air Data System

High performance military aircraft generally have a combined Pitot/static probe which extends out in front of the aircraft so as to be as far away as practicable aerodynamic interference effect and shock waves generated by the aircraft structure. Some civil transport aircraft have Pitot probes with seperate static pressure orifices located in the fuselage generally somewhere between the nose and the wing. The exact location of the static pressure orifices (and the Pitot tubes or probes) is determined by experience and experimentation.

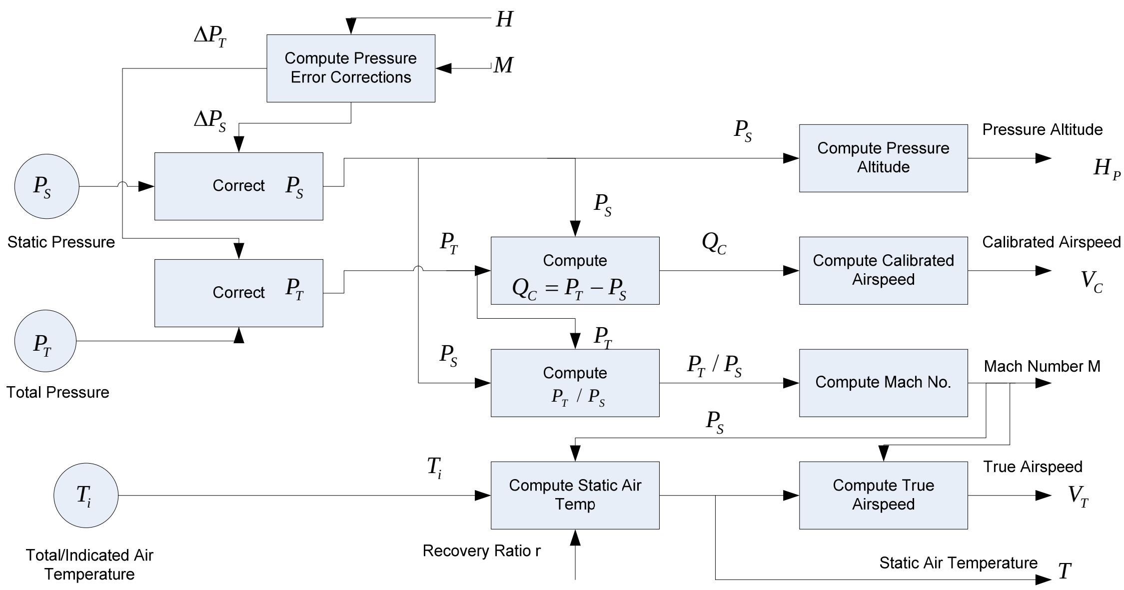

Figure 6.2: Air Data Computation Flow Diagram

From the measurements of the static pressure and total pressure it is possible to derive the following quantites.

1) Pressure altitude H_P; this is derived from the static pressure P_S measurement by assuming a ‘standard atmosphere’.
2) Vertical Speed $\dot{H}_P$, this is basically derived by differentiating P_S.
3) Calibrated airspeed V_C, this is derived directly from the impact pressure Q_C which is in turn derived from the difference between the total and static pressures ($Q_C = P_T - P_S$).
4) Mach number *M*, this is the ratio of the true airspeed V_T to the local speed of sound *A* that is $M = V_T / A$ and is derived directly from the ratio of the total pressure to the static pressure P_T / P_S .(True airspeed is defined as the speed of the aircraft relative to the air.)

6.2 Derivation of the True Air Speed components

The information obtained from the Air Data System is; true airspeed V_T, angle of attack α and yaw angle β. Using these datas the X, Y and Z components of the True Airspeed can be obtained[2].

$$\begin{aligned} V_x &= V_T (1 + \tan^2 \alpha + \tan^2 \beta)^{-1/2} \\ V_y &= V_T (1 + \tan^2 \alpha + \tan^2 \beta)^{-1/2} \tan \beta \\ V_z &= V_T (1 + \tan^2 \alpha + \tan^2 \beta)^{-1/2} \tan \alpha \end{aligned} \qquad \textbf{(6.1)}$$

These speeds are speeds according to the aircraft reference system. Later on, using the AHRS system these coordinates can be converted to ground based reference system for navigational usage.

7. KALMAN FILTER BASED INTEGRATION OF HELICOPTER AIR DATA SYSTEM WITH GLOBAL POSTIONING SYSTEM

The speed data of an aircraft is a very important parameter for flight systems of the aircraft. And it is desired that these parameters be very accurate. Navigation and flight management is accomplished using this speed data. There are many systems that provide the accurate speed data. However every speed data has its pros and cons. Some of them have inaccurate short-time speed data while having accurate overall speed data or some may have a less than desired sampling rate. For such reasons the integration of navigation systems has become a necessity. In this work, it is aimed to obtain a navigation system which has high measurement frequency and high accuracy. And for this purpose, the Air Data System which has high sampling rate and low speed accuracy is integrated with the Global Positioning System which has high accuracy but low sampling period. Using the known dynamic model of the system and the statistical data in the Kalman Filter, a more accurate integrated navigation system will be demonstrated.

7.1 Integrated Navigation Systems

In integrated navigation systems multiple sensor data are combined by spesific methods to obtain position, speed and altitude datas. Combination of sensor systems has become a necessity to improve the lacks of independent sensor systems.

In this work, we will try to explain how to achieve a more accurate and reliable navigation system by combining multi-sensor data via a filtering algorithm.

In general, navigation systems may rely on a few sensor data, depending on the complexity of the system. Some data may include the following:

- position and velocity data in geodetic coordinates, may be used to determine horizontal and vertical ground speeds and appropriate heading angles.
- Yaw, pitch and roll or heading angles may need coordinate convertion.

- Linear or angular accelerations or ratios in the air vehicle reference axis system.
- Pitch angle, yaw angle and air speed, for control matters.

Depending on the sensor characteristics, all state variables can not be achieved using a single sensor device. In a multi-sensor integrated navigation system, any individual sensor has at least one of the following features:

a) augmentation in navigation parameter error in time or in distance travelled. This is a feature of all Dead Reckoning based navigation sensors(Doppler vs..).
b) High noise of a derivable variable or narrow band width. This is a feature of radio navigation sensors, which need derivation in time, to obtain ratio or acceleration data. For instance in LORAN system, derivation of position gives the velocity. In Doppler; derivation of velocity provides us with the acceleration data. In all circumstances the state variables are converted to geocentric coordinates.

To overcome the lackings of sensors when used alone; the engineers have come up with the idea of combining the sensors. These multi-sensor systems have been designed to provide the dynamically accurate and reliable measurements at variable flight conditions.

In order to improve a known noisy sensor data with accordance to another more accurate sensor measurement data the Optimal Kalman Filter is applied. This KF requires error characteristics and the behaviour model of the system being observed, in order to reduce the errors.

7.2 Method Used in Integration

The purpose of this study is to integrate two navigation sources in the base of a Optimal Kalman Filter. Indirect Kalman Filter will be used here. Namely instead of system state variable estimates, the system's error estimates will be obtained by the Kalman Filter.

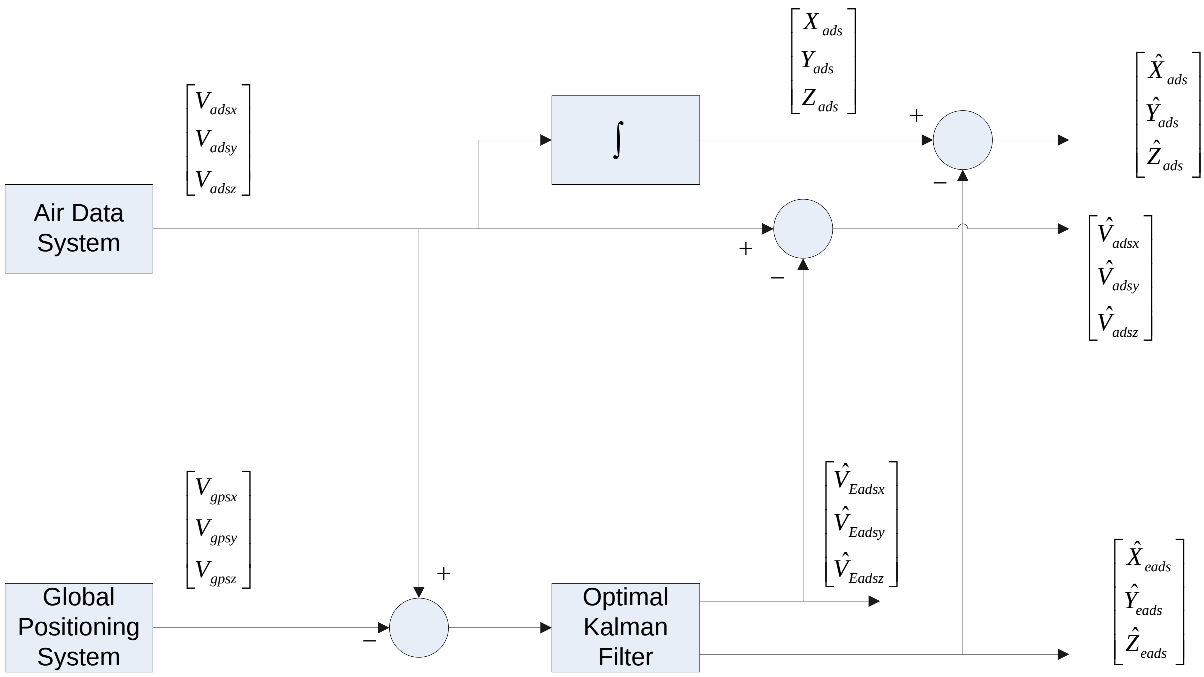

Figure 7.1: Integration of GPS and ADS schematics

The good features of both navigation systems are summed together in the integrated navigation system shown in figure(7.1). The following better uses have been obtained with this filter:

1) The high frequency of sampling feature of the Air Data System is used in the integrated system. On the other hand the GPS has a longer sampling period(1sec) than the ADS. Using the air speed and the filtered random error, a more accurate position data is aimed.
2) Using the difference between true air-speed and GPS speed a very accurate estimate of the wind speed is achieved.
3) In the integrated system; the error caused by the wind vector, which is included in the TAS of the ADS is filtered.

7.3 Necessary Parameters for the Kalman Filter

As seen in Figure (7.1) the difference of speeds obtained from each navigation system is introduced into the Kalman Filter. And the Kalman Filter outputs the Air Data System speed and position error estimate values.

The information we need for this filtering process are the system error models and the measurement error model.

The system error vector with required parameters is as follows,

$$x = \begin{bmatrix} X_{eads} & Y_{eads} & Z_{eads} & V_{eadsx} & V_{eadsy} & V_{eadsz} \end{bmatrix}^T \quad \textbf{(7.1)}$$

Here the X_{eads}, Y_{eads}, Z_{eads} are the position errors of Air Data System and V_{eadsx}, V_{eadsy}, V_{eadsz} are the speed errors of Air Data System, each in cartesian coordinates. In the Air Data System the True Air Speed error is mainly the result of the wind speed. Therefore choosing the Air Data System errors as the vector parameters shown in (7.1), is for the purpose of obtaining the true air speed error, which is relatively high, and thus the wind speed.

The uncorrelated model, which is used in exponential correlation function for the stagnant processes will be used[33,41]. This expression is in discrete and matrix form. This model is very suitable for simulation[42].

$$\begin{bmatrix} X_{eads}(k+1) \\ Y_{eads}(k+1) \\ Z_{eads}(k+1) \\ V_{eadsx}(k+1) \\ V_{eadsy}(k+1) \\ V_{eadsz}(k+1) \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 0 & T & 0 & 0 \\ 0 & 1 & 0 & 0 & T & 0 \\ 0 & 0 & 1 & 0 & 0 & T \\ 0 & 0 & 0 & 1-\beta_{V_{adsx}}T & 0 & 0 \\ 0 & 0 & 0 & 0 & 1-\beta_{V_{adsy}}T & 0 \\ 0 & 0 & 0 & 0 & 0 & 1-\beta_{V_{adsz}}T \end{bmatrix}}_{\phi} \begin{bmatrix} X_{eads}(k) \\ Y_{eads}(k) \\ Z_{eads}(k) \\ V_{eadsx}(k) \\ V_{eadsy}(k) \\ V_{eadsz}(k) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ (\beta_{V_{adsx}}T - \frac{1}{2}\beta^2{}_{V_{adsx}}T^2)w_{V_{adsx}} \\ (\beta_{V_{adsy}}T - \frac{1}{2}\beta^2{}_{V_{adsy}}T^2)w_{V_{adsy}} \\ (\beta_{V_{adsz}}T - \frac{1}{2}\beta^2{}_{V_{adsz}}T^2)w_{V_{adsz}} \end{bmatrix} \quad \textbf{(7.2)}$$

In (7.2) $\beta_{V_{adsx}}, \beta_{V_{adsy}}, \beta_{V_{adsz}}$ are the variables which are inverse to true air speed correlation time and $w_{V_{adsx}}, w_{V_{adsy}}, w_{V_{adsz}}$ are the Gauss distributed noises of the Air Data System speed measurements. T is the sampling period in (7.2).

Using the Air Data System and GPS speed measurement differences as measurements observation vector in the Kalman Filter, the observation vector can be stated as;

$$\begin{aligned} z_1(k) &= V_{eadsx} + v_{V_{adsx}} - v_{V_{gpsx}} \\ z_2(k) &= V_{eadsy} + v_{V_{adsy}} - v_{V_{gpsy}} \\ z_3(k) &= V_{eadsz} + v_{V_{adsz}} - v_{V_{gpsz}} \end{aligned} \quad \textbf{(7.3)}$$

In (7.3) $V_{eadsx,}\ V_{eadsy,}\ V_{eadsz}$ are the true air speed measurement errors of the Air Data System and at the same time are the wind speeds and $v_{V_{adsx}}, v_{V_{adsy}}, v_{V_{adsz}}$ and $v_{V_{gpsx}}, v_{V_{gpsy}}, v_{V_{gpsz}}$ are the zero-mean Gauss noises of the Air Data System and GPS respectively. Namely, the difference between the GPS speed measurement and the Air Data System true air speed measurement gives us the Air Data System speed error and the wind speed during flight. However, this wind speed information includes the random noises of both systems. The standard deviation of air data system true air speed is 2m/sec and standard deviation of Global Positioning System speed is 0.1 m/sec[1, 43]. If measurement statements of (7.3) are written in matrix form;

$$z(k) = \begin{bmatrix} z_1(k) \\ z_2(k) \\ z_3(k) \end{bmatrix} = \begin{bmatrix} V_{ADSX} - V_{GPSX} \\ V_{ADSY} - V_{GPSY} \\ V_{ADSZ} - V_{GPSZ} \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}}_{H(k)} x(k) + \begin{bmatrix} v_{Vx} \\ v_{Vy} \\ v_{Vz} \end{bmatrix} \quad \textbf{(7.4)}$$

To obtain the Air Data System true error values that will be used in the simulation, the system error model is used;

$$x_g(k+1) = \phi(k+1,k)x_g(k) \quad \textbf{(7.5)}$$

And solving (7.8) according to the initial values the true error values are obtained. Here ϕ is the transfer matrix of the system error model which describes the evolution of the system error at (7.2). The system's error vector for the true error values is;

$$x = \begin{bmatrix} X_{eg} & Y_{eg} & Z_{eg} & V_{egx} & V_{egy} & V_{egz} \end{bmatrix}^T \quad \textbf{(7.6)}$$

As seen on figure(7.1), the output of the Kalman Filter gives air data system speed error estimates which is wind speed estimates $\hat{V}_{eadsx}, \hat{V}_{eadsy}, \hat{V}_{eadsz}$ and connected with these, the position error estimates $\hat{X}_{eads}$, $\hat{Y}_{eads}$, $\hat{Z}_{eads}$ are obtained. Subtracting these error values from the measured speed values of the Air Data System; the estimated flight speeds $\hat{V}_{adsx}, \hat{V}_{adsy}, \hat{V}_{adsz}$ are obtained, and subtracting the Kalman Filter estimated position error from the integrated measured true air speed, we obtain the position estimates; $\hat{X}_{ads}$, $\hat{Y}_{ads}$, $\hat{Z}_{ads}$. And the ground speed estimates can be written as:

$$
\begin{aligned}
\hat{V}_{adsx} &= V_{adsx} - \hat{V}_{eadsx} \\
\hat{V}_{adsy} &= V_{adsy} - \hat{V}_{eadsy} \\
\hat{V}_{adsz} &= V_{adsz} - \hat{V}_{eadsz}
\end{aligned}
\tag{7.7}
$$

And position estimates:

$$
\begin{aligned}
\hat{X}_{ads} &= \int V_{adsx} dt - \hat{X}_{eads} \\
\hat{Y}_{ads} &= \int V_{adsy} dt - \hat{Y}_{eads} \\
\hat{Z}_{ads} &= \int V_{adsz} dt - \hat{Z}_{eads}
\end{aligned}
\tag{7.8}
$$

The true air speeds V_{adsx}, V_{adsy}, V_{adsz} in (7.8) are calculated by subtracting the true air speed error (the wind speed) obtained from the system error model, from, and summing the Gauss distributed random measurement noise which is proportional to the true air speed random error deviation, to V_x, V_y, V_z values obtained from the flight simulation:

$$
\begin{aligned}
V_{adsx} &= V_x - V_{egpsx} + \sigma_{V_{adsx}} randn \\
V_{adsy} &= V_y - V_{egpsy} + \sigma_{V_{adsy}} randn \\
V_{adsz} &= V_z - V_{egpsz} + \sigma_{V_{adsz}} randn
\end{aligned}
\tag{7.9}
$$

And the simulation of the measurement values of the GPS is achieved by summing the the product of the Gauss distributed noise and GPS speed error deviation, to the speeds obtained from the flight simulation which are assumed true flight speeds:

$$
\begin{aligned}
V_{gpsx} &= V_x + \sigma_{V_{gpsx}} randn \\
V_{gpsy} &= V_y + \sigma_{V_{gpsy}} randn \\
V_{gpsz} &= V_z + \sigma_{V_{gpsz}} randn
\end{aligned}
\tag{7.10}
$$

The measurement transfer matrix from expression (7.4) can be written as:

$$H = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad \textbf{(7.11)}$$

Since the system noise only involves speed errors, and position errors are formed from them, the noise transfer matrix can be written as:

$$G = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \textbf{(7.12)}$$

Noise correlation matrix *Q(k)* and measurement error correlation matrix *R(k)* can be taken as[4]:

$$Q(k) = \begin{bmatrix} 0.001 & 0 & 0 \\ 0 & 0.001 & 0 \\ 0 & 0 & 0.001 \end{bmatrix} \quad \textbf{(7.13)}$$

$$R(k) = \begin{bmatrix} \sigma^2_{V_{adsx}} + \sigma^2_{V_{gpsx}} & 0 & 0 \\ 0 & \sigma^2_{V_{adsy}} + \sigma^2_{V_{gpsy}} & 0 \\ 0 & 0 & \sigma^2_{V_{adsz}} + \sigma^2_{V_{gpsz}} \end{bmatrix} \quad \textbf{(7.14)}$$

As seen in (7.14) measurement error correlation matrix is a diagonal matrix, with; the sum of the random measurement variants of Air Data System and those of GPS composing the diagonal elements.

7.4 KF based Integrated ADS/GPS navigation system applied to helicopter dynamics

In the previous approach we took the differences of speed of Air Data System speed measurements and the Global Positioning System speed measurements, in which case we assumed the GPS data more accurate and thus considered this difference as the ADS error of speed, and introduced this [3x1] dimensional vector of speed error to the Optimal Kalman Filter. And to obtain the position information the speed information was integrated.

The GPS receiver we built and used provides us with the position information as well as speed. The ADS system provides us with only air speed of the aircraft which is obtained after processing of pitot-tube sensor information.

In this approach the air speed information of ADS is integrated at start and the ADS position is obtained. And the difference of position and speed of both navigation systems are used to obtain the state vector of Kalman Filter.

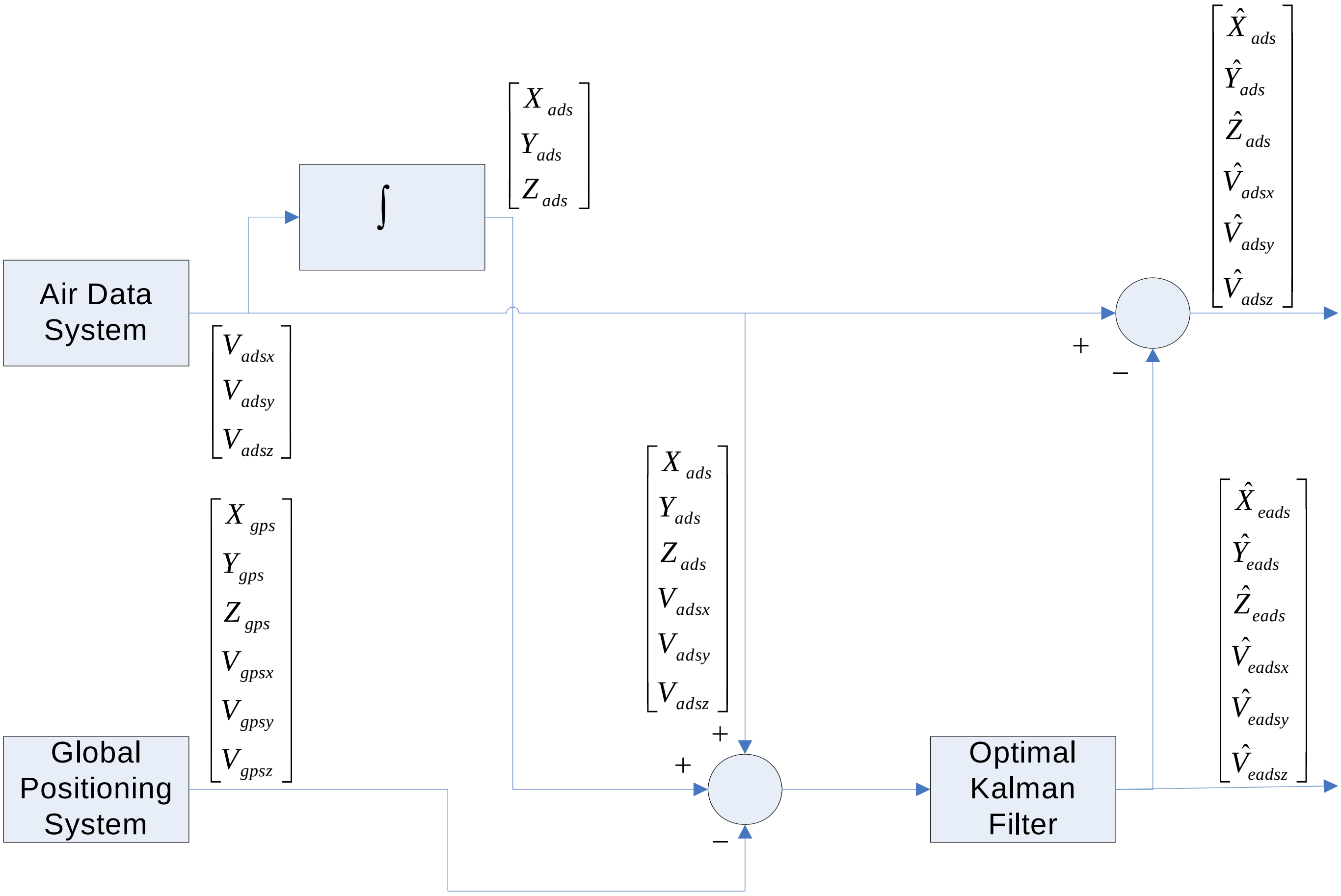

Figure 7.2: Integration of GPS and ADS schematics using both position and speed errors

Using the Air Data System and GPS speed measurement differences as measurements observation vector in the Kalman Filter, the observation vector can be stated as;

$$
\begin{aligned}
z_1(k) &= X_{eads} + v_{X_{ads}} - v_{X_{gps}} \\
z_2(k) &= Y_{eads} + v_{Y_{ads}} - v_{Y_{gps}} \\
z_3(k) &= Z_{eads} + v_{Z_{ads}} - v_{Z_{gps}} \\
z_4(k) &= V_{eadsx} + v_{V_{adsx}} - v_{V_{gpsx}} \\
z_5(k) &= V_{eadsy} + v_{V_{adsy}} - v_{V_{gpsy}} \\
z_6(k) &= V_{eadsz} + v_{V_{adsz}} - v_{V_{gpsz}}
\end{aligned} \tag{7.15}
$$

In (7.15) $V_{eadsx,}\ V_{eadsy,}\ V_{eadsz}$ are the true air speed measurement errors of the Air Data System and at the same time are the wind speeds and $v_{V_{adsx}}, v_{V_{adsy}}, v_{V_{adsz}}$ and $v_{V_{gpsx}}, v_{V_{gpsy}}, v_{V_{gpsz}}$ are the zero-mean Gauss noises of the Air Data System and GPS respectively. Namely, the difference between the GPS speed measurement and the Air Data System true air speed measurement gives us the Air Data System speed error and the wind speed during flight. However, this wind speed information includes the random noises of both systems. The standard deviation of air data system true air speed is 2m/sec and standard deviation of Global Positioning System speed is 0.1 m/sec[1, 43]. If measurement statements of (7.15) are written in matrix form;

$$
z(k) = \begin{bmatrix} z_1(k) \\ z_2(k) \\ z_3(k) \\ z_4(k) \\ z_5(k) \\ z_6(k) \end{bmatrix} = \begin{bmatrix} X_{ADS} - X_{GPS} \\ Y_{ADS} - Y_{GPS} \\ Z_{ADS} - Z_{GPS} \\ V_{ADSX} - V_{GPSX} \\ V_{ADSY} - V_{GPSY} \\ V_{ADSZ} - V_{GPSZ} \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}}_{H(k)} x(k) + \begin{bmatrix} v_X \\ v_Y \\ v_Z \\ v_{Vx} \\ v_{Vy} \\ v_{Vz} \end{bmatrix} \tag{7.16}
$$

In this approach the measurement transfer matrix becomes [6x6] unity matrix since we consider both position and speed.

$$
H = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{7.17}
$$

Since the system noise involves both speed errors and position errors, the noise transfer matrix can be written as:

$$G = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad \textbf{(7.18)}$$

Noise correlation matrix *Q(k)* and measurement error correlation matrix *R(k)* can be taken as[4]:

$$Q(k) = \begin{bmatrix} 0.001 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.001 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.001 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.001 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.001 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.001 \end{bmatrix} \qquad \textbf{(7.19)}$$

The first three diagonals of the correlation matrix *R(k)* are obtained by summing the squares of the Air Data System position error deviation and Global Positioning System position error deviation:

$$R(k) = \begin{bmatrix} \sigma^2_{X_{ads}} + \sigma^2_{X_{gps}} & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma^2_{Y_{ads}} + \sigma^2_{Y_{gps}} & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma^2_{Z_{ads}} + \sigma^2_{Z_{gps}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma^2_{V_{adsx}} + \sigma^2_{V_{gpsx}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma^2_{V_{adsy}} + \sigma^2_{V_{gpsy}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma^2_{V_{adsz}} + \sigma^2_{V_{gpsz}} \end{bmatrix}$$

(7.20)

7.5 SIMULATION

7.5.1 Flight Simulation Parameters

The equations of motion that will be used in the flight dynamics simulation are[44];

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{7.21}$$

Here x is the vector matrix that contains the state variables, y is called the output vector, u is the control or input vector, A is the state matrix, B is the input matrix or control matrix, C is the output matrix, and D is the feedforward matrix. Combining the longitudinal and lateral flight dynamics equations of motion in a single matrix form, we obtain;

$$A = \begin{bmatrix} -0.07 & -0.017 & 16.62 & -18.4 & 0.001 & -1 & 0.02 & -0.07 & 000 \\ 0.04 & -0.65 & 0.14 & -1.39 & -0.04 & 0.07 & -0.33 & -0.03 & 000 \\ 0.01 & 0.007 & -2.72 & -2.22 & 0.0002 & 0.15 & -0.001 & -0.04 & 000 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 000 \\ -0.007 & -0.006 & -0.97 & 0.005 & -0.14 & -6.91 & 22.3 & 3.76 & 000 \\ -0.0006 & 0.003 & -0.81 & 0.001 & -0.014 & -4.56 & -6.26 & 0.63 & 000 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 000 \\ 0.007 & 0.015 & -0.55 & 0.0001 & 0.014 & -1.03 & -0.92 & -3.68 & 000 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 000 \\ 0 & 0 & 0 & 0 & U0 & 0 & 0 & 0 & 000 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 000 \end{bmatrix} \tag{7.22}$$

$$B = \begin{bmatrix} -2.2 & 0.54 & 0 & 0.0001 \\ -0.01 & -12.1 & -314.45 & 0 \\ 0.36 & -0.003 & -0.01 & 0.008 \\ 0 & 0 & 0 & 0 \\ -0.034 & -0.17 & 1.18 & -1 \\ 0.093 & -0.098 & 1.09 & -0.25 \\ 0 & 0 & 0 & 0 \\ 0.25 & 0.04 & 0.04 & 0.73 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{7.23}$$

The state vector including the flight state variables is;

$$x = [u \;\; w \;\; q \;\; \theta \;\; v \;\; p \;\; \phi \;\; r \;\; X \;\; Y \;\; Z]^T \qquad \textbf{(7.24)}$$

The variables in the state vector (6.24) are;

u:flight speed in direction X(m/sec)

w:flight speed in direction Z(m/sec)

q:pitch angular speed(degree/sec)

θ:pitch angle(degree)

β :yaw angle(degree)

ϕ :roll angle(degree)

p:roll angular speed(degree/sec)

r:yaw angular speed(degree/sec)

Using equations (7.21) - (7.24) of flight dynamics, we can calculate the changes of the values of the state vector. The above equations are in real-time form. In the simulation discrete-time form will be use.

$$x(k+1) = A(k)x(k) + B(k)u(k) \qquad \textbf{(7.25)}$$

The C matrix in the output equation is a [11x11] unity matrix and the D matrix is assumed zero.

True airspeed x,y,z Standard deviations [1,43]

$$\sigma_{V_{adsx}} = 2[m/s], \sigma_{V_{adsy}} = 2[m/s], \sigma_{V_{adsz}} = 2[m/s]$$

GPS x,y,z speed standard deviations [1,43]

$$\sigma_{V_{gpsx}} = 0.1[m/s], \sigma_{V_{gpsy}} = 0.1[m/s], \sigma_{V_{gpsz}} = 0.1[m/s]$$

Air data system x,y,z speeds correletaion times and their inverses [33]

$$\tau c_{Vx} = 600[s], \tau c_{Vy} = 600[s], \tau c_{Vz} = 600[s]$$

$$\beta_{Vx} = 1/600[s^{-1}], \beta_{Vy} = 1/600[s^{-1}], \beta_{Vz} = 1/600[s^{-1}]$$

Sampling time is taken T=0.001[sec] in the simulation.

System Transfer matrix in discrete form,

$$\phi(k+1,k) = \begin{bmatrix} 1 & 0 & 0 & 0.001 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0.001 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0.001 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Covariant matrix initial value;

$$P(0) = \begin{bmatrix} 100 & 0 & 0 & 0 & 0 & 0 \\ 0 & 100 & 0 & 0 & 0 & 0 \\ 0 & 0 & 100 & 0 & 0 & 0 \\ 0 & 0 & 0 & 10 & 0 & 0 \\ 0 & 0 & 0 & 0 & 10 & 0 \\ 0 & 0 & 0 & 0 & 0 & 10 \end{bmatrix}$$

Error vector initial values for the real error model,

$$x(0,0) = [0.1\ \ 0.1\ \ 0.1\ \ 7\ \ 5\ \ 1.7]^T$$

Error vector initial values for the Kalman Filter error model,

$$x(0,0) = [0.1\ \ 0.1\ \ 0.1\ \ 12\ \ 7\ \ 5]^T$$

6.5.2 Simulation Results

After running the MATLAB code the following graphics are obtained to show the integration results. Some graphics are shown here, the rest are placed to the appendix part.

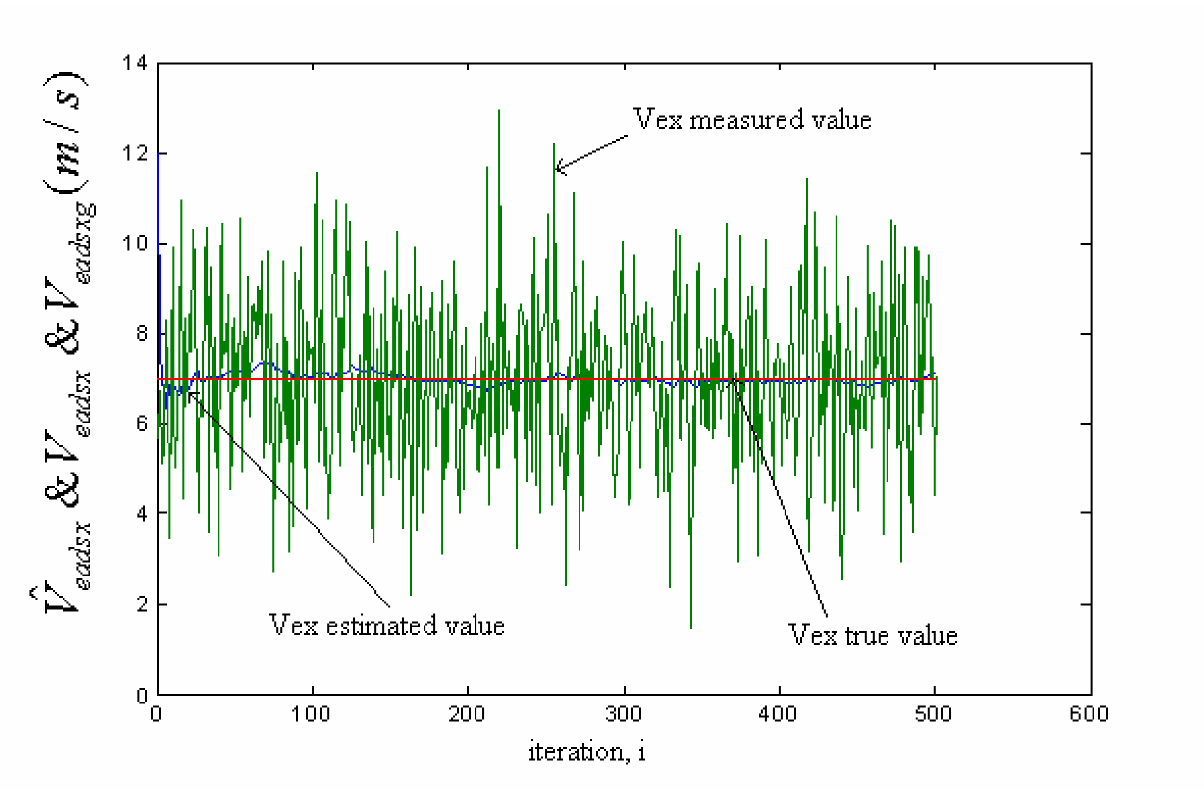

Figure 7.3: V_{eadsx} wind speed error measured value, true error value and estimated error value

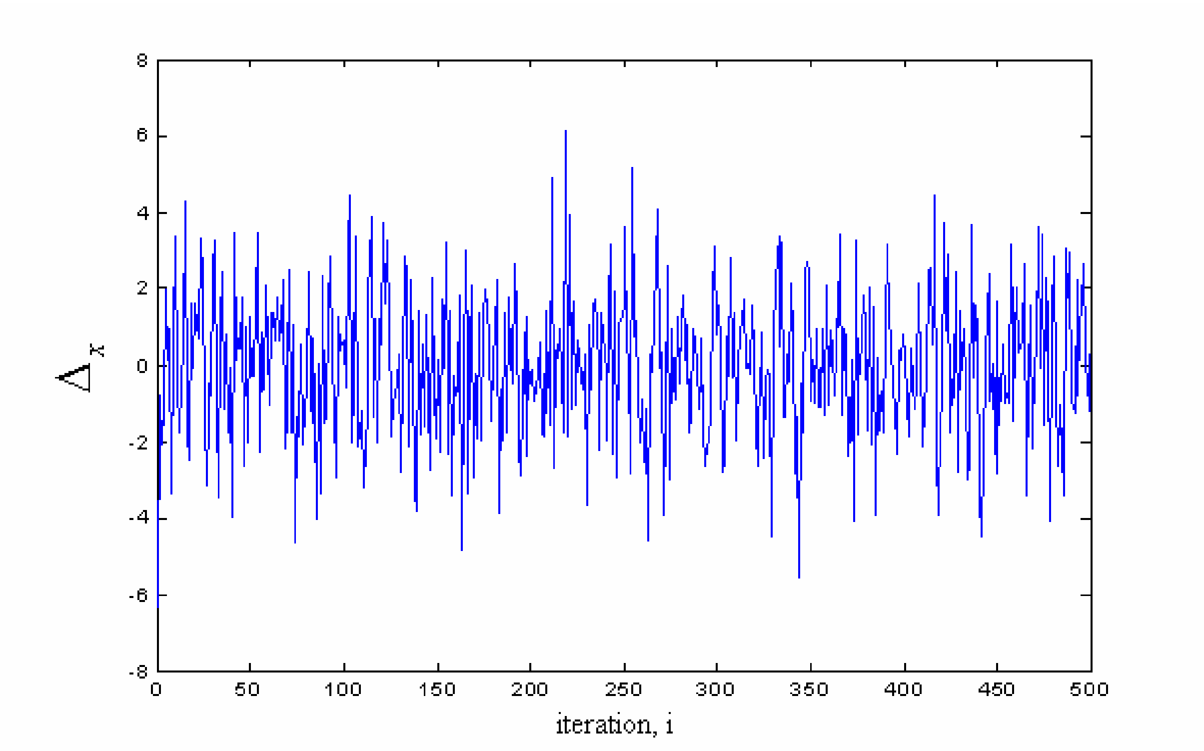

Figure 7.4: Innovation process for V_{eadsx} wind speed

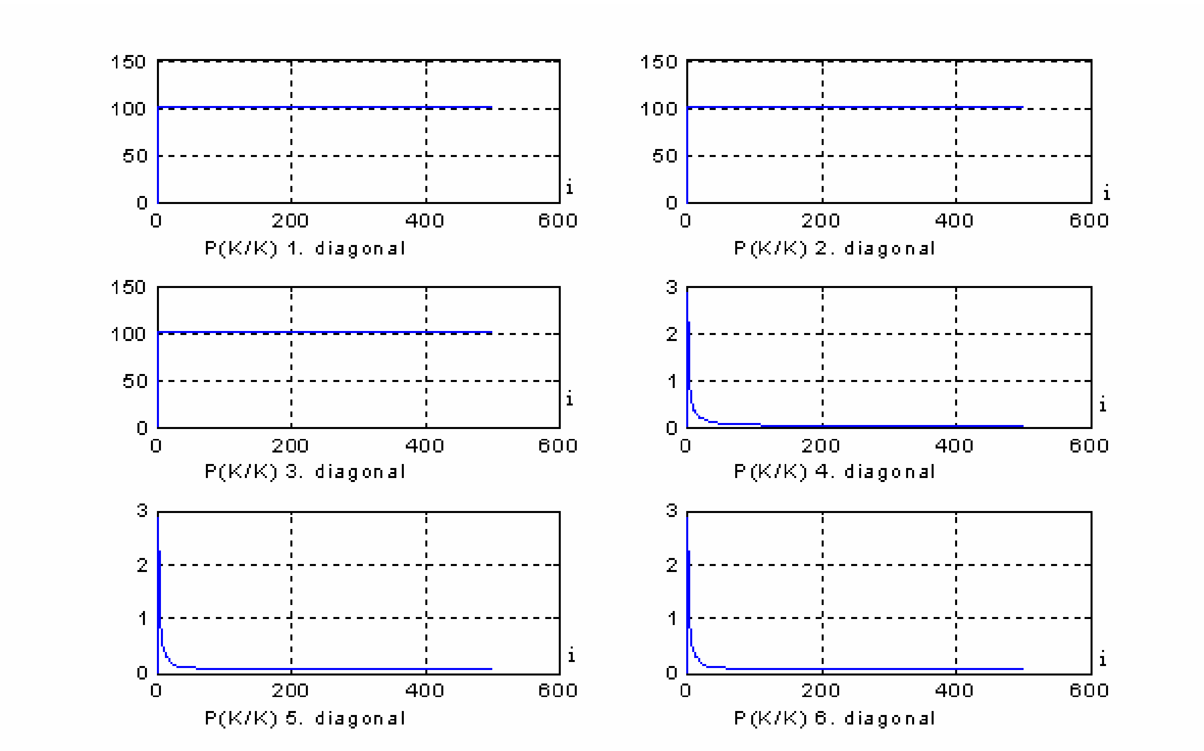

Figure 7.5: Variants of Air Data speeds and positions

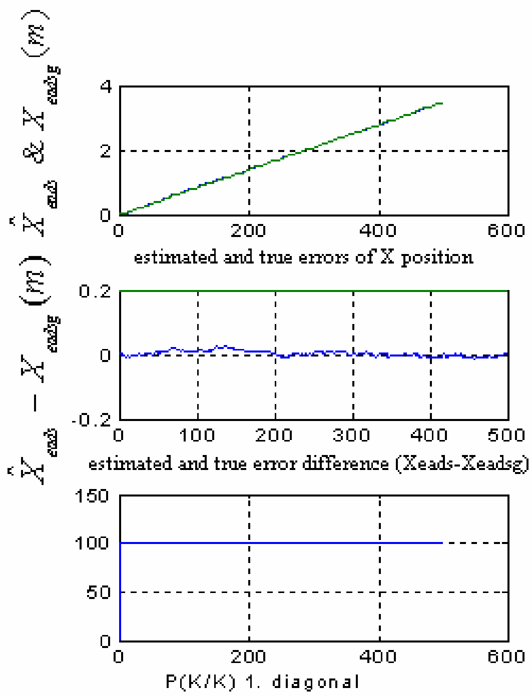

Figure 7.6: X position estimated error , absolute error and P(k/k) 1st diagonal

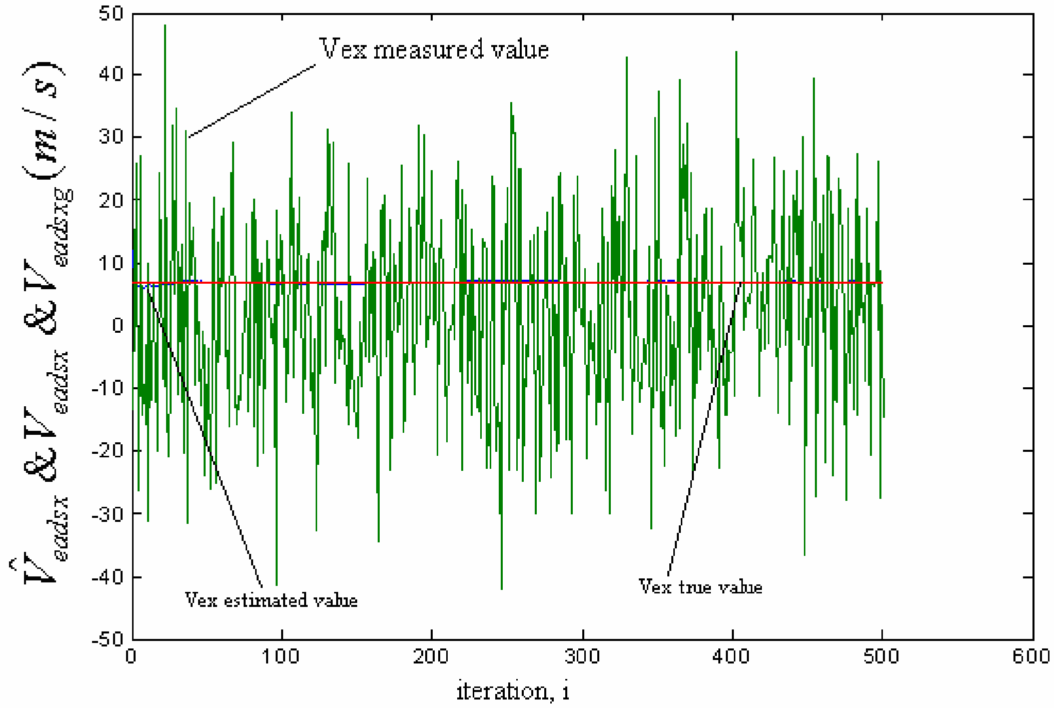

Figure 7.7: V_{eadsx} wind speed error measured value, true error value and estimated error value when position and speed errors included

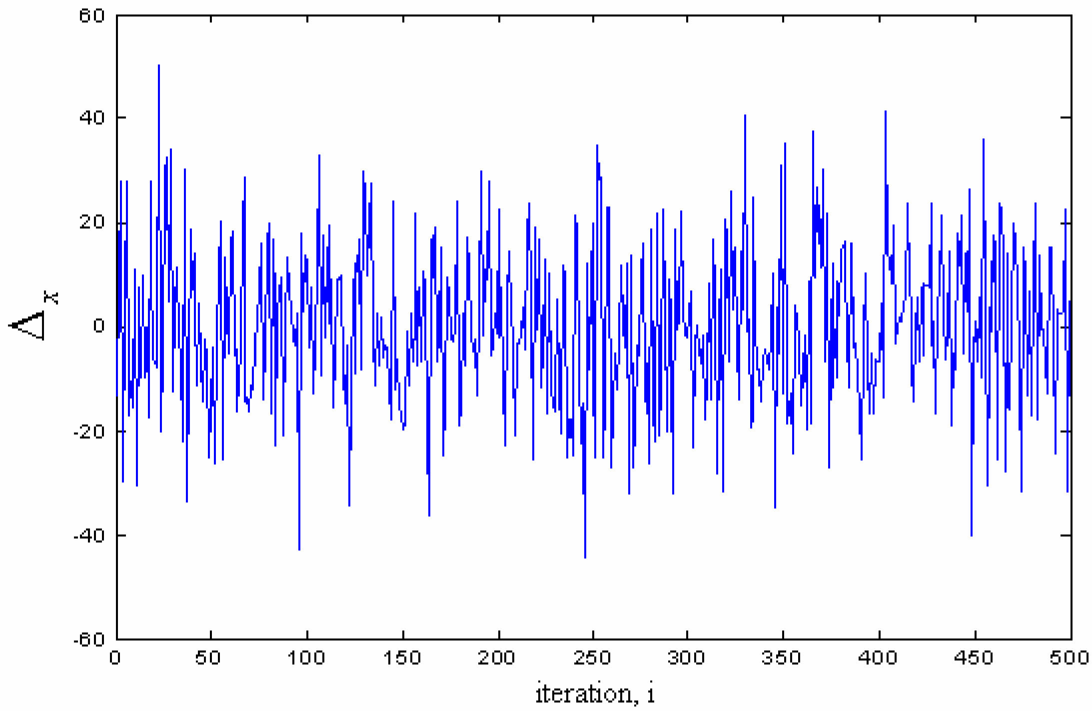

Figure 7.8: Innovation process for V_{eadsx} wind speed, when position and speed errors used in KF

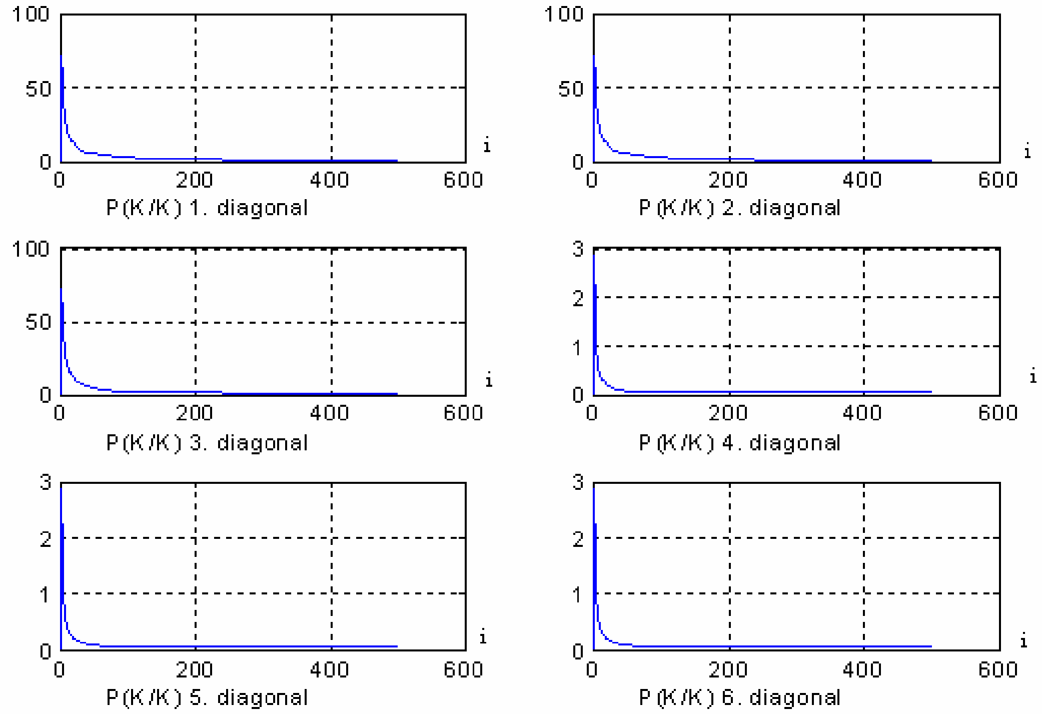

Figure 7.9: Position and speed variants, when position and speed errors used in KF

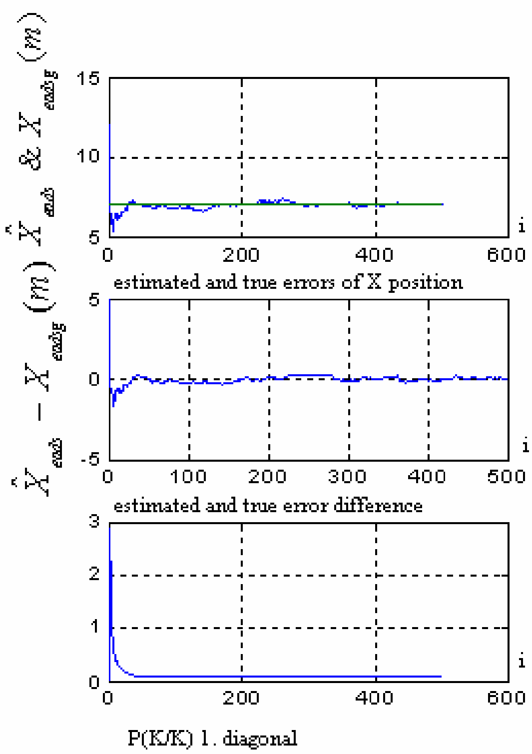

Figure 7.10: X position error estimate, true error and P(k/k) 1st diagonal when position and speed errors included

The position and speed estimates obtained by the Optimal Kalman Filter for all the state variables are very close to the true error values. This convergence remains in all iterations, which states that the Kalman Filter is working properly. The position and speed measurements of both measurement systems is subtracted from each other and applied to the Kalman Filter. As a result the position and speed errors of the Air Data System are calculated by the Kalman Filter. Here, very small GPS errors are not included to the process. The true air speed error obtained by the Kalman Filter gives us the wind speed meanwhile. In figure 7.3 and figure 7.7 air speed error in direction *X*, true air speed error and estimated air speed errors are shown. As seen the estimated air speed error remains very close to the true air speed error. The wind speed error calculated by the Kalman Filter is around 0.2 m/sec, and is very superior compared to the noise measurement values. In figures 7.4 and 7.8 the innovation processes in direction *X* are shown. In figures 7.5 and 7.9 the variances of the error estimates obtained from the diagonal elements of the covariance matrix *P(k/k)* are shown. In figures 7.6 and 7.10 the position and speed error estimates and true errors in direction *X* of the Air Data System are shown. In these figures the decline of the difference of the error estmate and the true error during time as well as the change in the corresponding covariance can be seen. Other graphics and tables can be seen at the Appendix part.

8.CONCLUSION

The purpose of this work was to improve the aircraft navigation systems using Kalman Filter. In the first part the GPS system is improved using Satellite Distances Method. The GPS receiver used in this part provides us with the available satellite positions, the azimuth and elevation of the satellite. Using the satellite positions and the position of the GPS receiver, a new model based on the distances between the satellites and the GPS receiver was used. In year 2000 the SA restriction to civilian users was reduced and position error has reduced from 100 meters to 30 meters. In our work we succeeded to reduce the position error to less than 1 meter.

In the second part, integration of navigation systems is objected, the integrated navigation system has the adventages of both navigation systems, in this study we integrated Air Data System with Global Positioning System, in which ADS has poor accuracy and high sampling frequency, while GPS has high accuracy and low sampling rate. Kalman Filter was used to minimize the speed and position errors. Wind speed error has been reduced to 0.1m/s and related position error has been reduced to around 0.001 m. Obtained position values remained close to the real position values.

In the first part we used the Kalman Filter to improve the position output of a commercially available GPS receiver, using the satellites and receiver position informations.

- The GPS receiver horizontal position deviation was given as 13m and vertical position deviation as 22m. After applying the Kalman Filter based Satellite Distances Method to the real GPS measurements, both the horizontal and vertical position deviations have reduced to less then 1m.
- This study was not simulation, real GPS receiver data was used. What does that mean? In simulation Zero-Mean Gauss noise is added to the observation vector. However we used the measured data as it is. Which makes this study a real-time application.

- In the second part we integrated two navigation systems,the Air Data System and the Global positioning System, in the base of an Optimal Kalman Filter. The Air Data System has high sampling frequency, however poor speed measurement accuracy, on the other hand GPS has low sampling frequency(1Hz) and superior position and speed accuracy compared to the ADS.

- Since GPS is reliable to the satellites, it can not be relied on alone. And since ADS is not reliable on an outer system we can trust it all the way, however ADS speed error is enormous and can not be trusted for DR positioning purposes. By this integration of ADS with GPS, the calibration of ADS is established. And ADS alone can be used for DR navigation.

- This integration provides us with the ADS air speed error; which is the wind speed. The GPS speed and ADS air data speeds are differenced and applied to the Kalman Filter, this process has provided us with a very accurate wind speed.

- The KF based ADS and GPS integration can improve to much better if KF based satellite distances method is applied first to the GPS measurements.

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APPENDIX

APPENDIX A

COORDINATE SYSTEMS CONVERSION OF GPS POSITIONS

A.1 ECEF Coordinate System

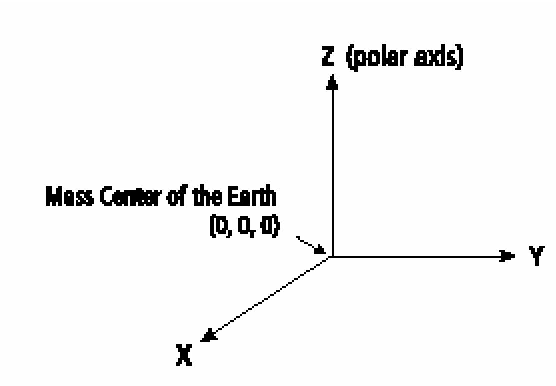

Figure A.1: ECEF Coordinate Reference Frame

The Cartesian coordinate frame of reference used in GPS is called Earth-Centered, Earth- fixed (ECEF). ECEF uses three-dimensional XYZ coor-dinates (in meters) to describe the location of a GPS user or satellite. The term "Earth-Centered" comes from the fact that the origin of the axis (0,0,0) is located at the mass center of gravity (determined through years of tracking satellite trajectories). The term "Earth-Fixed" implies that the axes are fixed with respect to the earth (that is, they rotate with the earth). The Z-axis pierces the North Pole, and the XY-axis defines the equatorial plane. (Figure A.1) ECEF coordinates are expressed in a reference system that is related to mapping representa-tions.

Because the earth has a complex shape, a simple, yet accurate, method to approximate the earth's shape is required. The use of a reference ellipsoid allows for the conversion of the ECEF coordinates to the more commonly used geodetic-mapping coordinates of Latitude, Longitude, and Altitude (LLA). Geodetic coordinates can then be converted to a second map reference known as Mercator

Projections, where smaller regions are projected onto a flat mapping surface (that is, Universal Transverse Mercator – UTM or the USGS Grid system).

A reference ellipsoid can be described by a series of parameters that define its shape and which include a semi-major axis (a), a semi-minor axis (b) and its first eccentricity e)andits second eccentricity (e') as shown in Figure A.2. Depending on the formulation used, ellipsoid flattening (f) may be required.

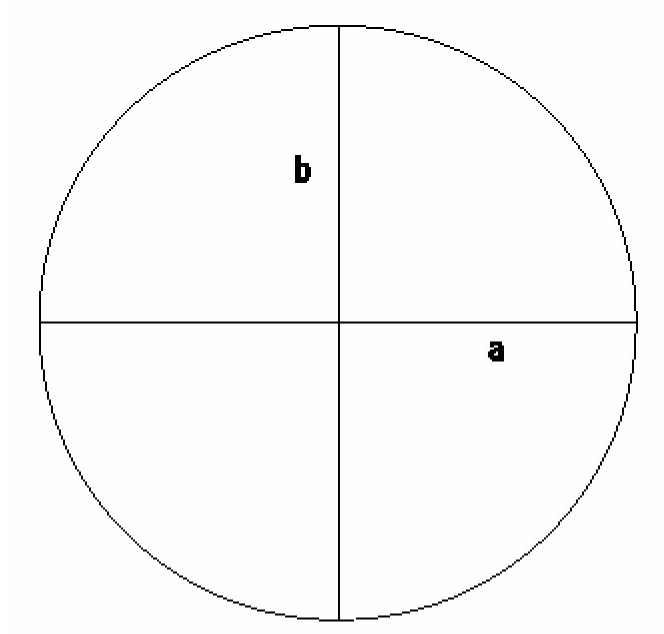

Figure A.2: Ellipsoid Parameters

WGS84 Parameters:

$$
\begin{aligned}
a &= 6378137 \\
b &= a(1-f) \\
&= 6356752.31424518 \\
f &= \frac{1}{298.257223563} \\
e &= \sqrt{\frac{a^2-b^2}{a^2}} \\
e' &= \sqrt{\frac{a^2-b^2}{a^2}}
\end{aligned}
$$

For global applications, the geodetic reference (datum) used for GPS is the World Geodetic System 1984 (WGS84). This ellipsoid has its origin coincident with the

ECEF origin. The X-axis pierces the Greenwich meridian (where longitude = 0 degrees) and the XY plane make up the equatorial plane (latitude=0 degrees). Altitude is described as the perpendicular distance above the ellipsoid surface (which not to be confused with the mean sea level datum).

A.2 Conversion between ECEF and Local Tangential Plane

A.2.1 LLA to ECEF

The conversion between the two reference coordinate systems can be performed using closed formulas (although iteration methods also exist). The conversion fromLLA to ECEF (in meters) is shown below.

$$X = (N + h)\cos\varphi\cos\lambda$$
$$Y = (N + h)\cos\varphi\cos\lambda$$
$$Z = (\frac{b^2}{a^2}N + h)\sin\varphi$$

where:

$\varphi =$ Latitude

$\lambda =$ Longitude

$h =$ height above ellipsoid(meters)

$N =$ Radius of Curvature(meters),defined as:

$$= \frac{a}{\sqrt{1 - e^2 \sin^2\varphi}}$$

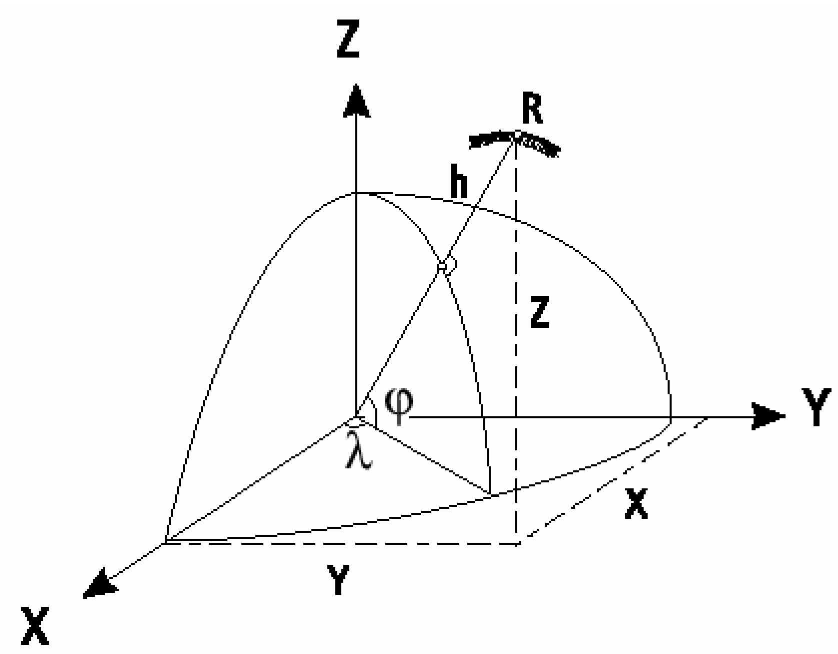

Figure A.3: ECEF and Reference Ellipsoid

A.2.2 ECEF to LLA

The conversion between XYZ and LLA is slightly more involved but can be achieved using one of the following methods:

By iteration for φ and h. There is quick convergence for h $\langle\langle$ N starting at $h_0 = 0$.

$$\lambda = \arctan \frac{Y}{X}$$

Start with $h_0 = 0$

$$\varphi_0 = \arctan \frac{Z}{p(1-e^2)}$$

Iterate φ and h

$$N_i = \frac{a}{\sqrt{1-e^2 \sin^2 \varphi_i}}$$

$$h_{i+1} = \frac{p}{\cos \varphi_i} - N_i$$

$$\varphi_{i+1} = \arctan \frac{Z}{p(1 - e^2 \frac{N_i}{N_i + h_{i+1}})}$$

Or by closed formula set.

$$\lambda = \arctan \frac{Y}{X}$$

$$\varphi = \arctan \frac{Z + e'^2 b \sin^3 \theta}{p - e^2 a \cos^3 \theta}$$

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

Where auxiliary values are:

$$p = \sqrt{X^2 + Y^2}$$

$$\theta = \arctan \frac{Za}{pb}$$

These equations are used in MATLAB programs in order to convert Geodetic coordinates to Descartes coordinates.

APPENDIX B

KALMAN BASED IMPROVEMENT OF GPS MEASUREMENTS USING SATELLITE DISTANCES METHOD

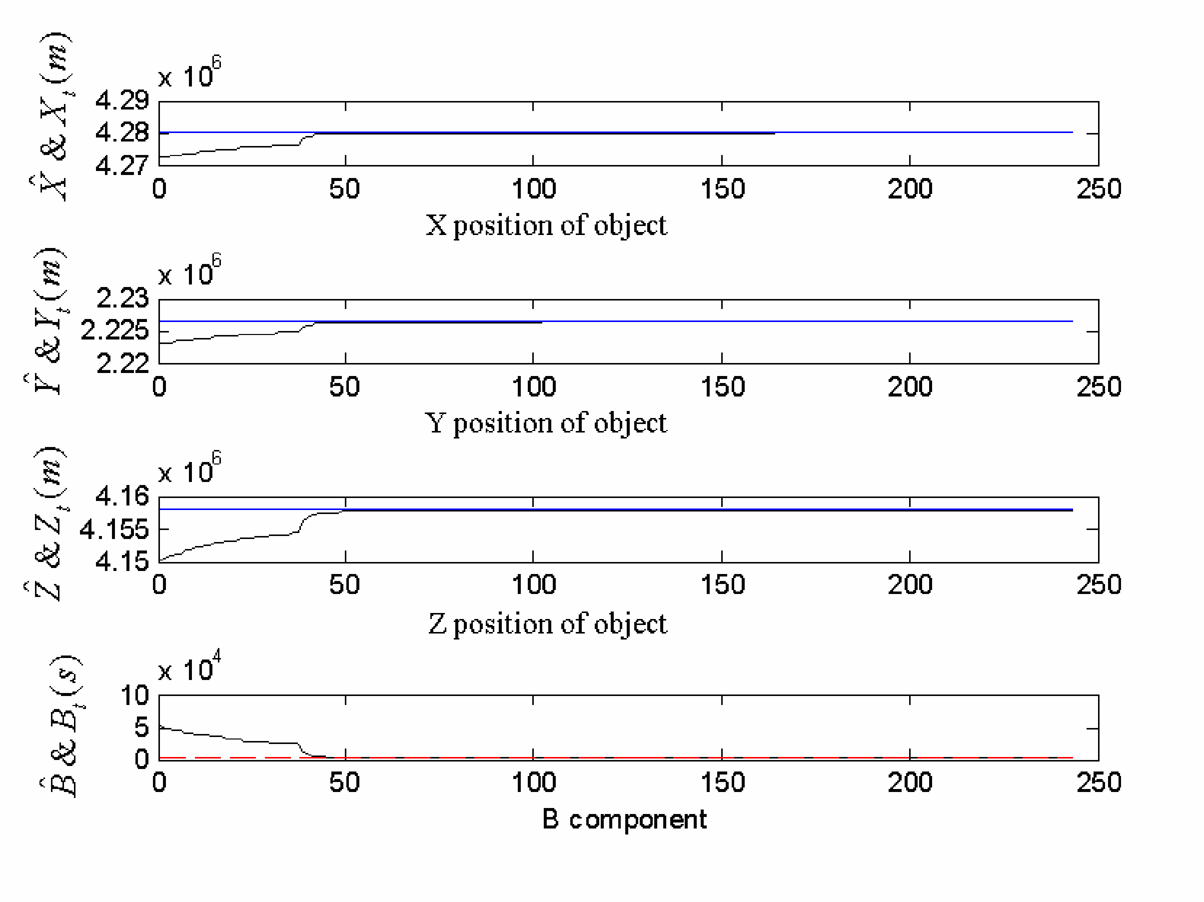

Figure B.1: Kalman Filter estimates and real positions when 5 satellites involved

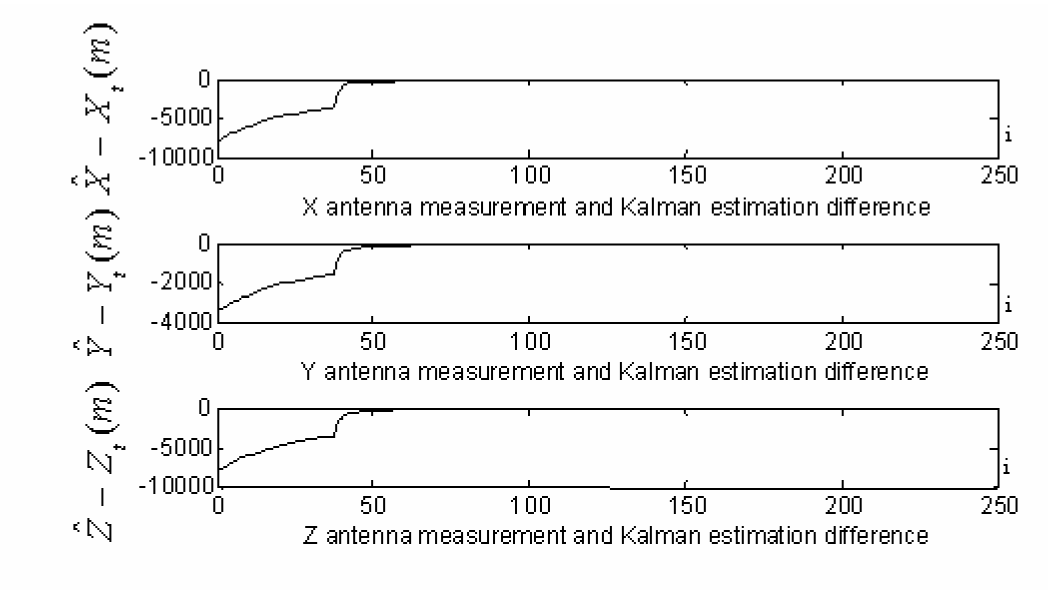

Figure B.2: Differences between true position and and KF estimation when 5 satellites in view

Table B.1: Error between GPS antenna real position and Kalman Filter estimations when 5 satellites available

Measurement and Estimation Step	X Error Between Antenna Measurement and KF Estimation(m)	Y Error Between Antenna Measurement and KF Estimation(m)	Z Error Between Antenna Measurement and KF Estimation(m)	B Error Between Antenna Measurement and KF Estimation(m)
25	-4439,35167	-1932,070249	-4364,031015	28641,37807
50	-319,6159012	-145,9814209	-311,6724678	2050,306843
75	-145,5934063	-69,3381855	-140,9877117	928,7425761
100	-103,2305258	-50,11396674	-100,1289447	658,0049075
125	-81,24488288	-39,73814207	-78,9452241	518,0714969
150	-66,8360742	-32,37786122	-64,32686736	424,4260759
175	-57,11415349	-27,70094086	-54,27409373	361,0254804
200	-46,41709258	-23,01504207	-43,80404146	291,3991832
225	-37,81616545	-19,32981168	-34,56994251	231,7171072
243	-34,43456373	-17,90688821	-31,91062942	211,6295776

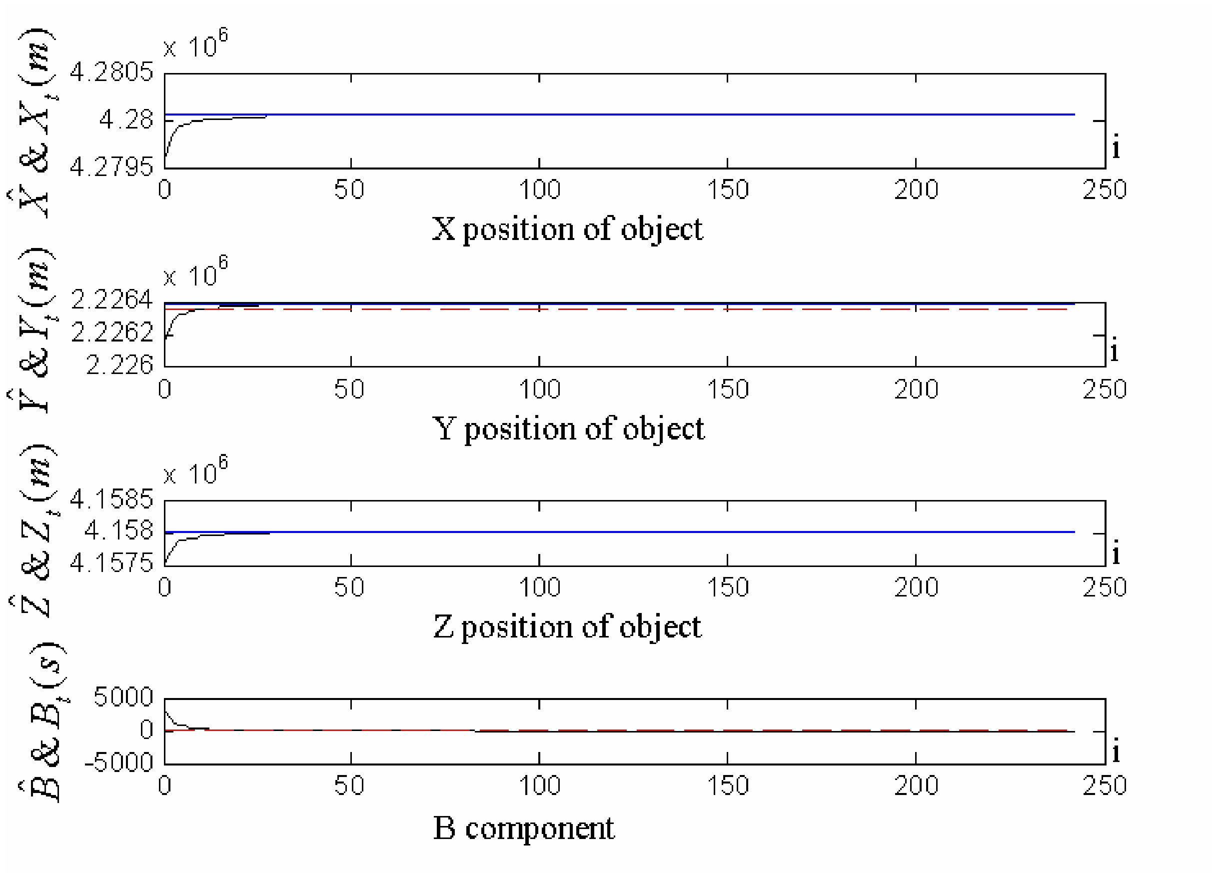

Figure B.3: Kalman Filter estimates and real positions when 6 satellites involved

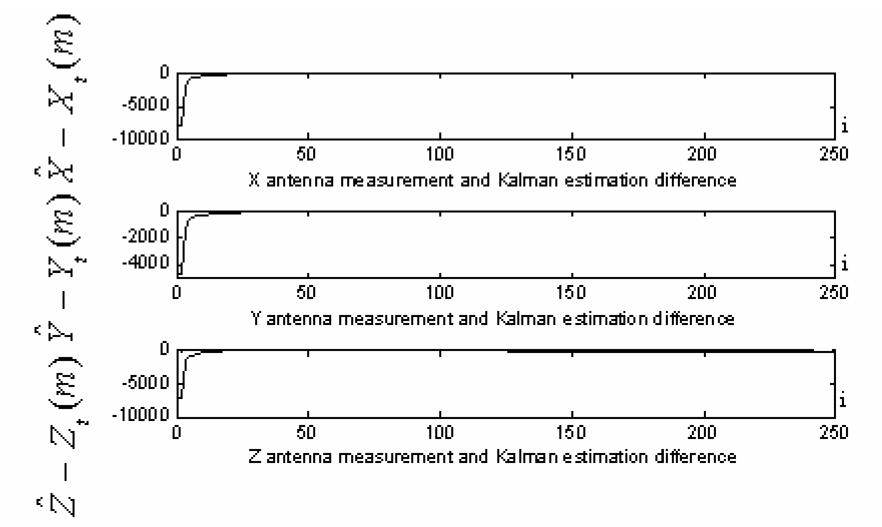

Figure B.4: Differences between true positions and position estimates

Table B.2: Error between GPS antenna real position and Kalman Filter estimations when 6 satellites available

Measurement and Estimation Step	X Error Between Antenna Measurement and KF Estimation(m)	Y Error Between Antenna Measurement and KF Estimation(m)	Z Error Between Antenna Measurement and KF Estimation(m)	B Error Between Antenna Measurement and KF Estimation(m)
25	-178,6348441	-109,7886098	-159,472809	1075,765286
50	-89,75302234	-55,45229172	-79,63259908	539,9658352
75	-60,07493213	-37,187903	-53,08343156	360,9997072
100	-32,97872188	-20,20448423	-29,55368643	201,4848464
125	-22,26694095	-13,78739485	-19,8840676	136,6262247
150	-16,90097582	-10,67203725	-15,38914232	105,0260338
175	-14,99991924	-9,535486318	-13,48389053	92,9162827
200	-14,0311075	-8,818678141	-12,57977888	86,7040766
225	-13,13614814	-8,198472583	-11,96953952	81,6212689
243	-11,38656196	-6,977264259	-10,33150866	70,42244851

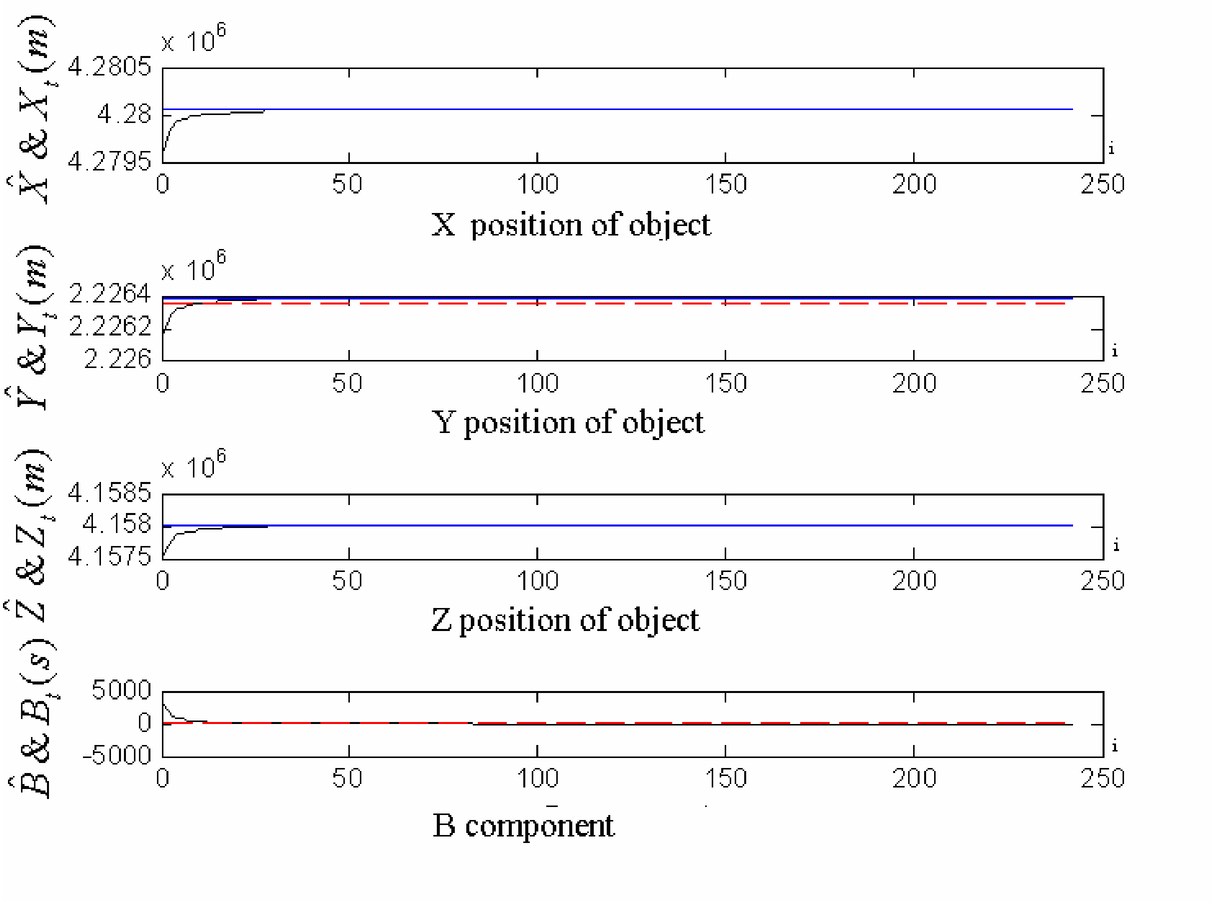

Figure B.5: Kalman Filter estimates and real positions when 7 satellites involved

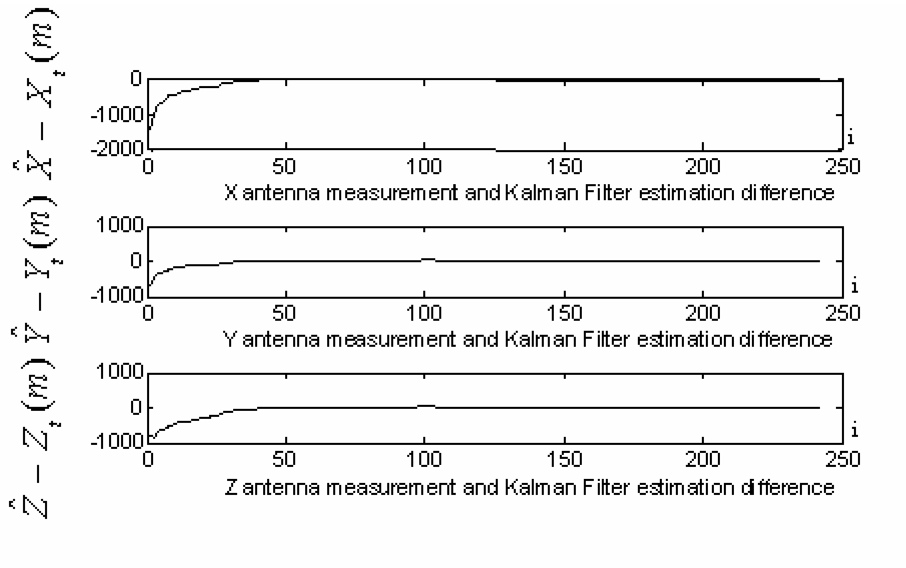

Figure B.6: differences between true position and and KF estimation

Table B.3: Error between GPS antenna real position and Kalman Filter estimations when 7 satellites available

Measurement and Estimation Step	X Error Between Antenna Measurement and KF Estimation(m)	Y Error Between Antenna Measurement and KF Estimation(m)	Z Error Between Antenna Measurement and KF Estimation(m)	B Error Between Antenna Measurement and KF Estimation(m)
25	-215,9961755	-111,668397	-251,3051388	1437,62403
50	-29,09952811	-12,80134375	-25,08473151	158,1809065
75	-11,06433589	-3,525764063	-6,679339756	46,06807497
100	-3,872332451	0,207228072	0,362009077	2,17523459
125	-6,627905249	-1,916122854	-4,769329359	29,22011131
150	-5,574963753	-1,38390216	-4,068171558	24,08904827
175	-4,659145107	-0,936278349	-3,390197835	19,30851283
200	-3,900109275	-0,993837318	-2,833785953	16,22428303
225	-3,46313896	-0,884336954	-2,479580691	14,30375516
243	-3,053213263	-0,737634358	-2,354576274	12,84939859

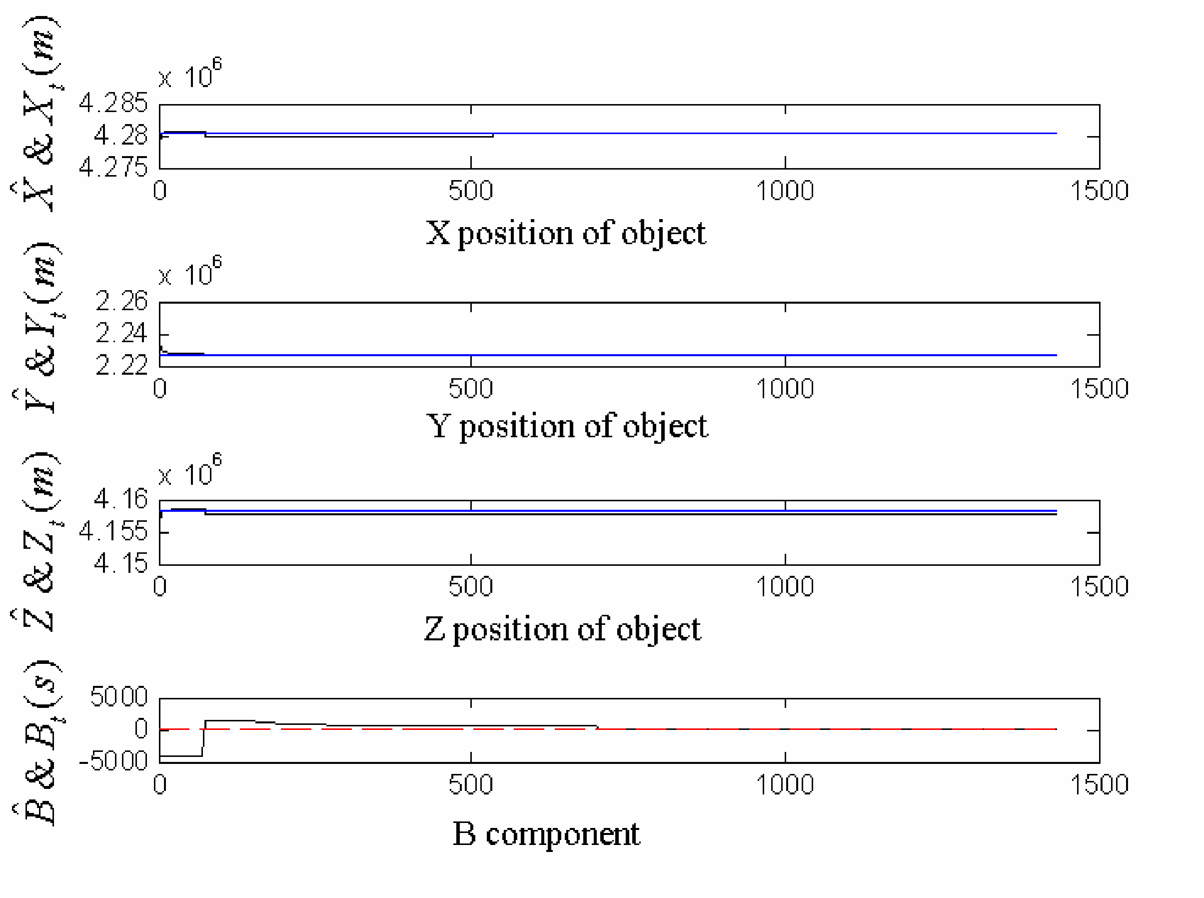

Figure B.7: Kalman Filter estimates and real positions when 4,5,6,7 satellite position data are combined

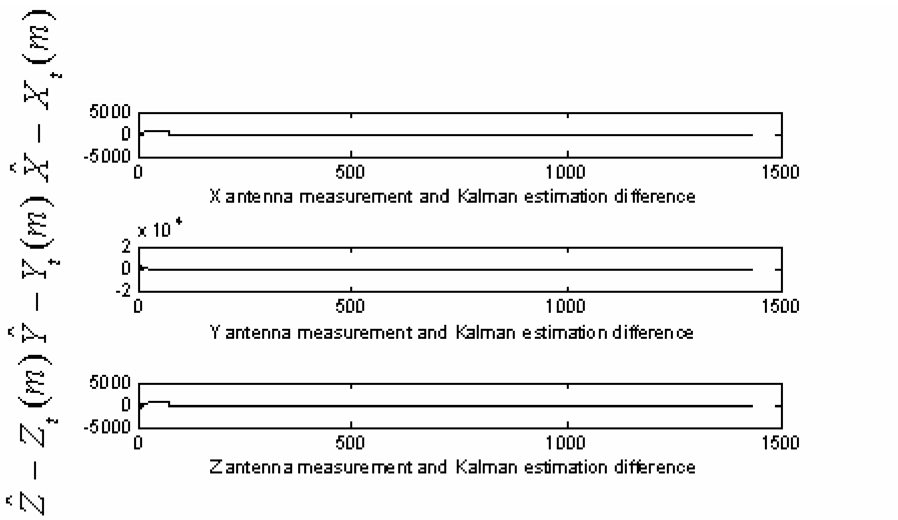

Figure B.8: Differences between true position and KF estimation when 4,5,6,7 satellite position data are combined

Table B.4: Error between GPS antenna real position and Kalman Filter estimations when ALL (4,5,6 and 7) satellites data integrated

Measurement and Estimation Step	X Error Between Antenna Measurement and KF Estimation(m)	Y Error Between Antenna Measurement and KF Estimation(m)	Z Error Between Antenna Measurement and KF Estimation(m)	B Error Between Antenna Measurement and KF Estimation(m)
25	643,6077328	776,5461802	509,2433207	-4332,785935
50	652,6042493	746,8148699	519,2724124	-4335,081005
75	-25,73025432	-1,412786801	-21,10361587	126,8489388
100	-29,1680491	-5,069891888	-22,94198794	146,7388841
125	-28,8014433	-4,915589162	-22,509767	144,2163803
150	-28,22286204	-4,577101909	-23,11063348	143,7082989
175	-14,97260297	-4,409709095	-16,18427292	91,99055107
200	-10,96523555	-4,26920337	-14,09986745	76,27631289
225	-9,098317268	-3,95391433	-12,93211352	68,14814695
250	-7,378861263	2,557685429	-11,35933113	65,54782149
275	-6,693482391	3,297238774	-9,9041395	57,98362251
300	-5,321963855	3,442618538	-8,43884724	50,27975988
325	-3,66248051	3,528319593	-6,827533987	41,57352206
350	-2,026167475	3,710972563	-5,280719575	32,68454347
375	0,61067956	4,459246141	-3,024331763	17,56469003
400	3,485843155	5,384097786	-0,054242133	-0,861675135
425	5,869663994	6,191622673	2,218115909	-15,6682618
450	6,282746604	5,810288848	2,142851283	-16,89450396
475	1,456545501	-3,576937537	4,892308702	-6,76518614
500	2,831589144	-2,584658416	6,005263641	-16,36809738
525	2,961979841	-2,126394621	6,144747237	-18,34707163
550	2,803333388	-1,818218411	5,834799766	-17,80975041
575	2,926111952	-1,540862	5,303837927	-17,37247978
600	2,976308405	-1,306513138	4,849420483	-17,00220022
625	2,214326191	-1,232419827	5,220828514	-16,40948172
650	1,793440719	-1,362190335	5,228795473	-15,43874316
675	1,338450816	-1,464352122	5,210611533	-13,90636573
700	1,035726178	-1,777194065	5,199590989	-12,16243754
725	5,890928189	-3,884288515	5,778718047	-3,782464631
750	3,022743442	-5,278886755	3,24778571	12,15285352
775	0,437845611	-6,542861502	1,220240492	25,78406318
800	-1,686240984	-7,602179076	-0,585741486	37,10321282
825	-3,455033328	-8,697923091	-2,065218292	46,31298621
850	-4,987591988	-9,660573311	-3,575061828	54,98054513
875	-6,322759295	-10,66661003	-4,975637268	63,03986885
900	-7,515623467	-11,25970054	-6,193390351	69,77527466
925	-8,58089957	-11,7792177	-7,276777337	75,77757192
950	-9,372854731	-12,15018191	-8,324622391	80,77924424
975	-13,81172647	-11,55166549	-2,736571332	76,60758448
1000	-13,13469526	-11,18490484	-2,897551776	74,05411542
1025	-11,37197108	-10,10451074	-2,100061782	64,79965896
1050	-9,776839291	-9,14684044	-1,45351205	56,67027507
1075	-8,613574169	-8,131922527	-0,852153506	49,8512121

1100	-8,774130133	-8,074320464	-1,71347059	52,36305435
1125	-9,043275656	-7,934400198	-2,34943308	54,44131468
1150	-9,188518381	-7,898926529	-2,907497331	56,11820593
1175	-8,329334566	-7,177605208	-2,459275771	51,37712516
1200	-6,344605329	-5,384727032	-2,702005679	43,66813543
1225	-4,946113754	-4,61049363	-1,647386314	35,34677333
1250	-3,388190811	-3,761800412	-0,717762685	26,82135902
1275	-2,163163174	-3,247772327	0,087247587	20,10768216
1300	-1,153035107	-2,848265339	0,43208433	15,48952259
1325	-0,683062344	-2,573722094	0,252755735	14,12379786
1350	-0,388188777	-2,395743185	0,17197079	13,13398849
1375	-0,293965218	-2,32811294	0,161580736	12,67645523
1400	-0,455788023	-2,718421783	-0,195891	14,47920727
1425	-0,612256254	-2,787919672	-0,660000482	16,10806904

APPENDIX C

KALMAN FILTER BASED INTEGRATED ADS/GPS NAVIGATION SYSTEM

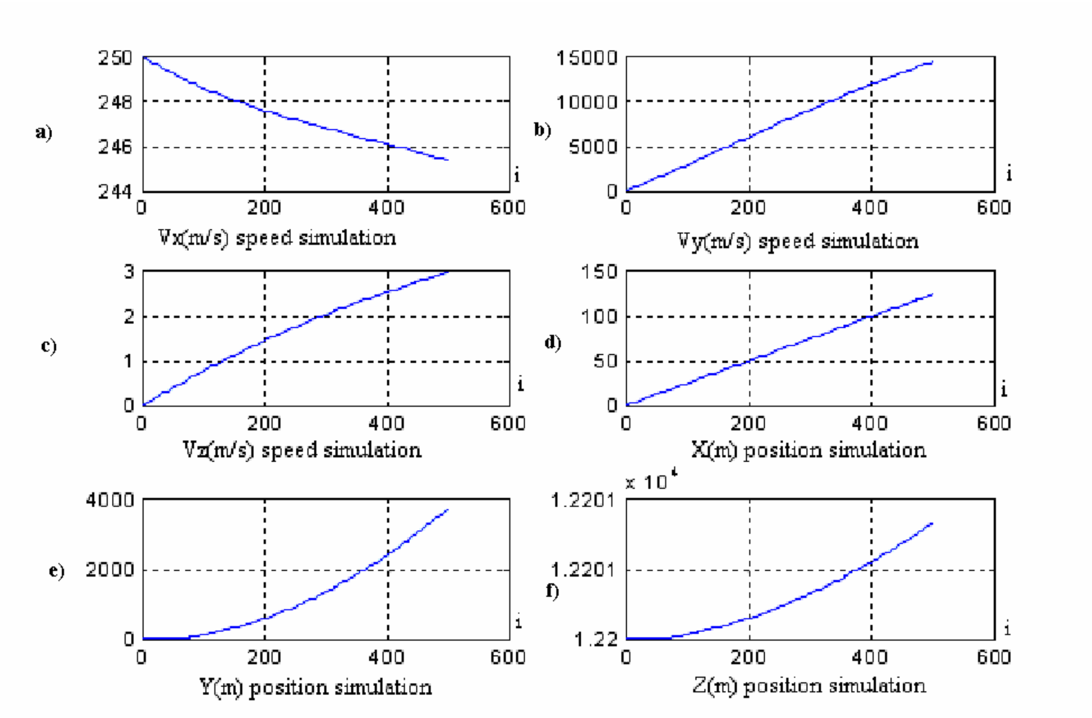

Figure C.1: Speed(a,b,c) and Position(d,e,f) simulations

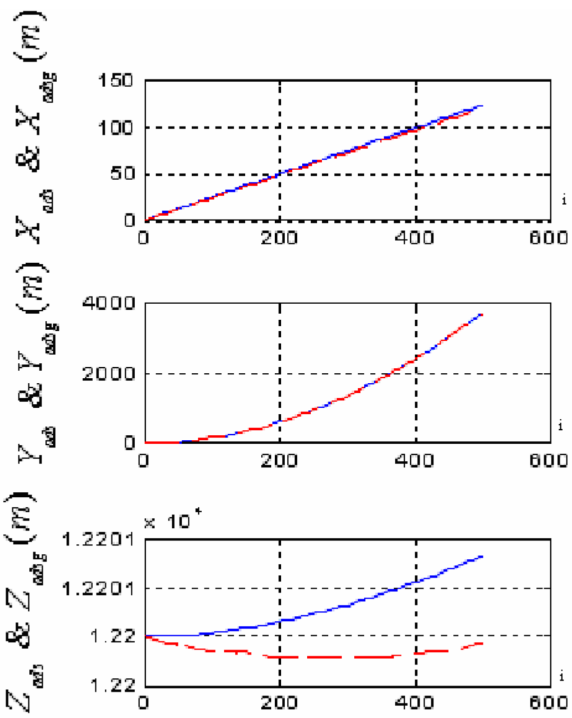

Figure C.2: ADS calculated positions and true positions(dashed lines)

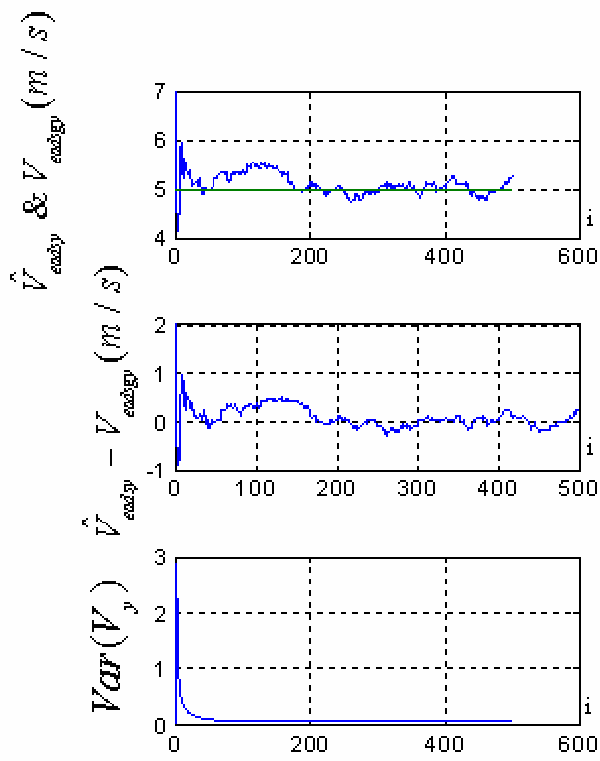

Figure C.3: Y speed error estimate and true error, their differences and variance of V_y

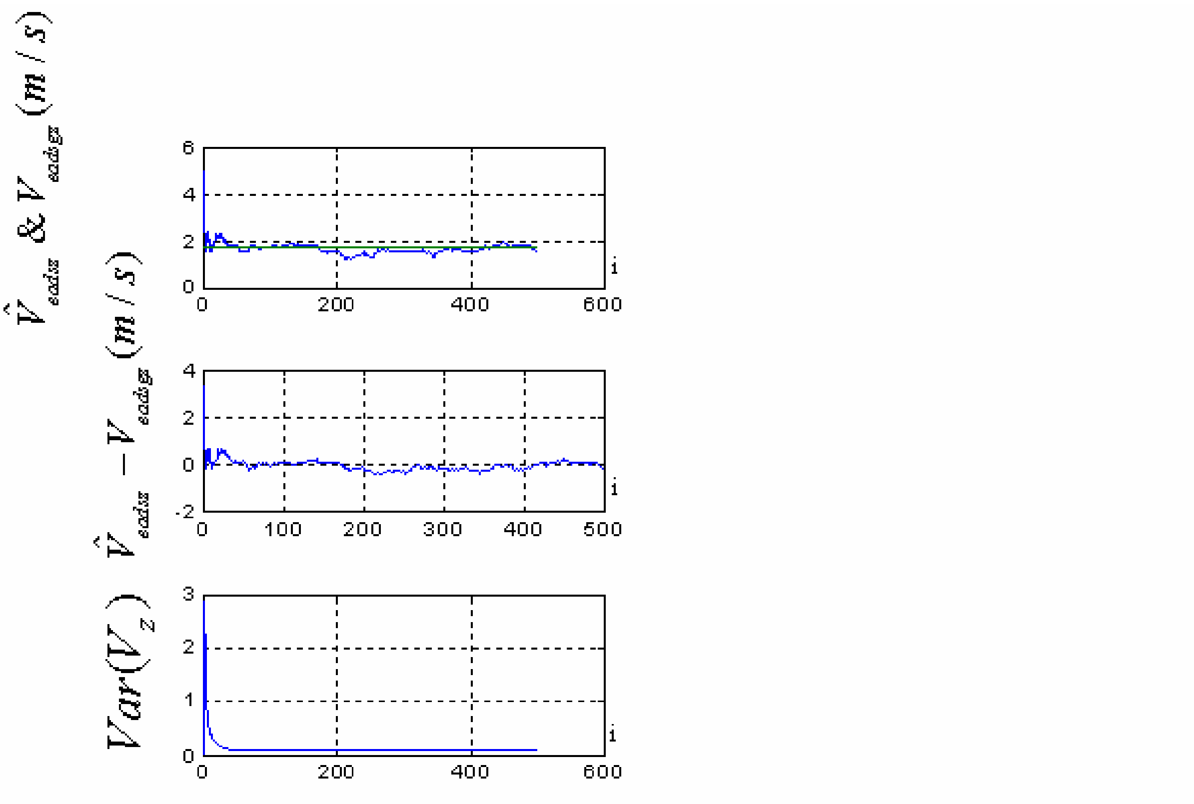

Figure C.4: Z speed error estimate, true error, their differences and variance of V_z

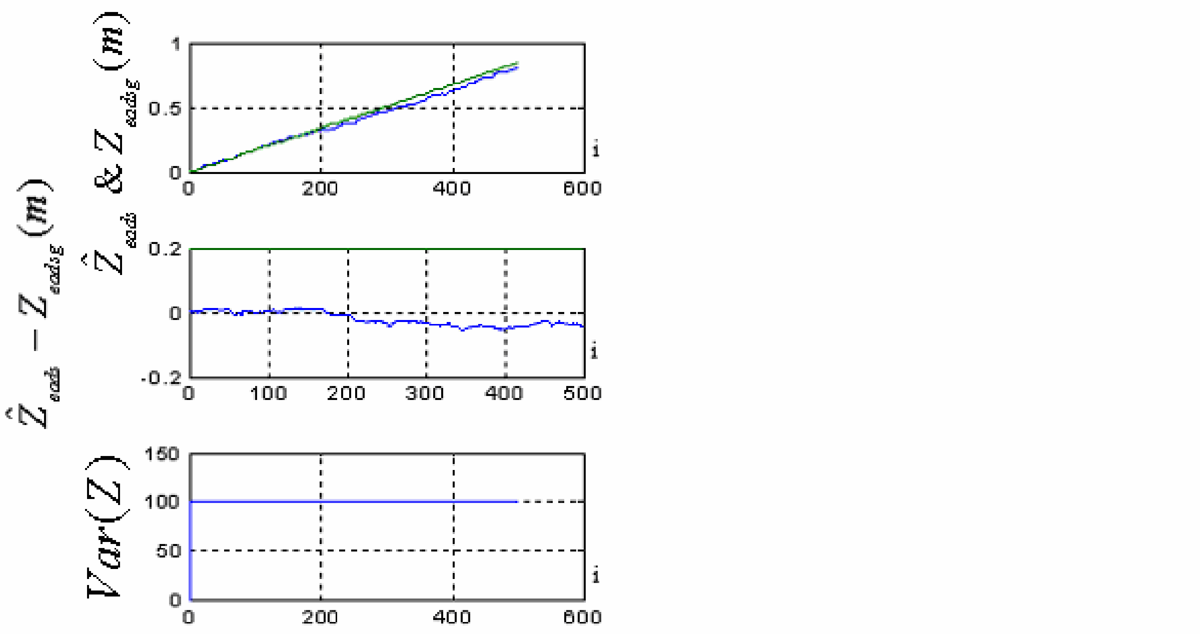

Figure C.5: Z position error estimate, true error, their differences and variance of Z

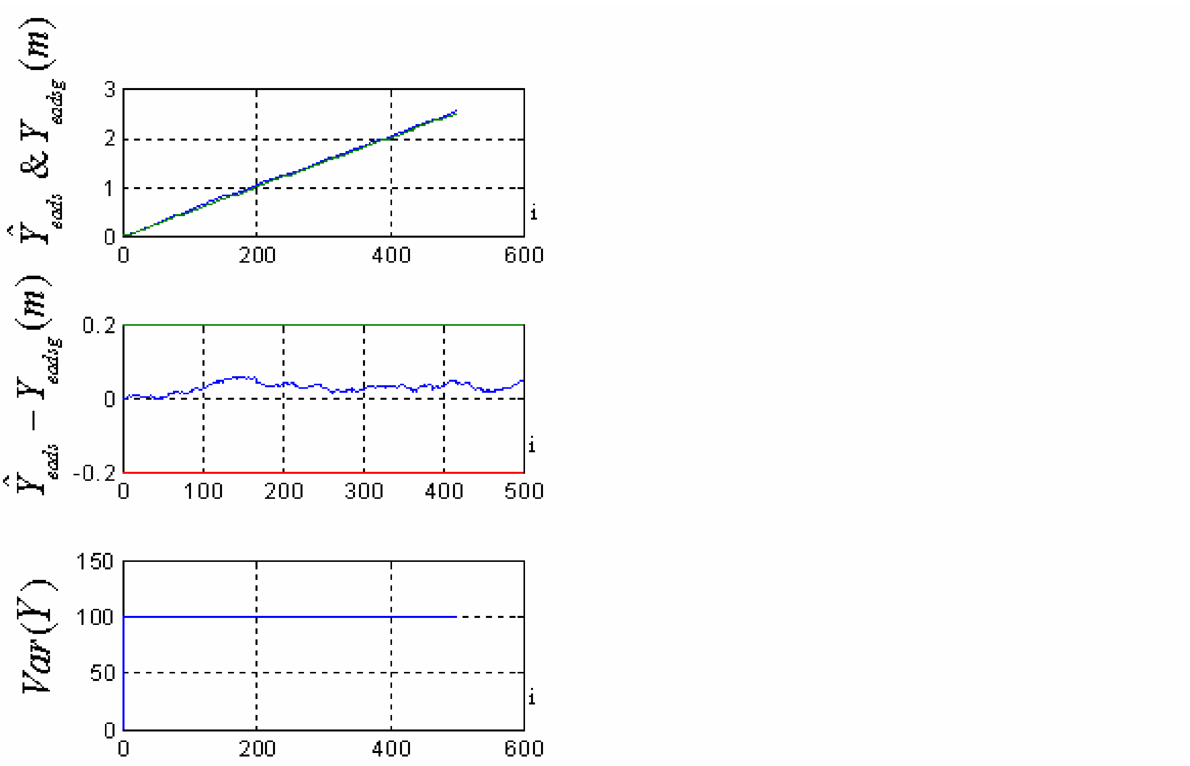

Figure C.6: Y position error estimate, true error, their differences and variance of Y

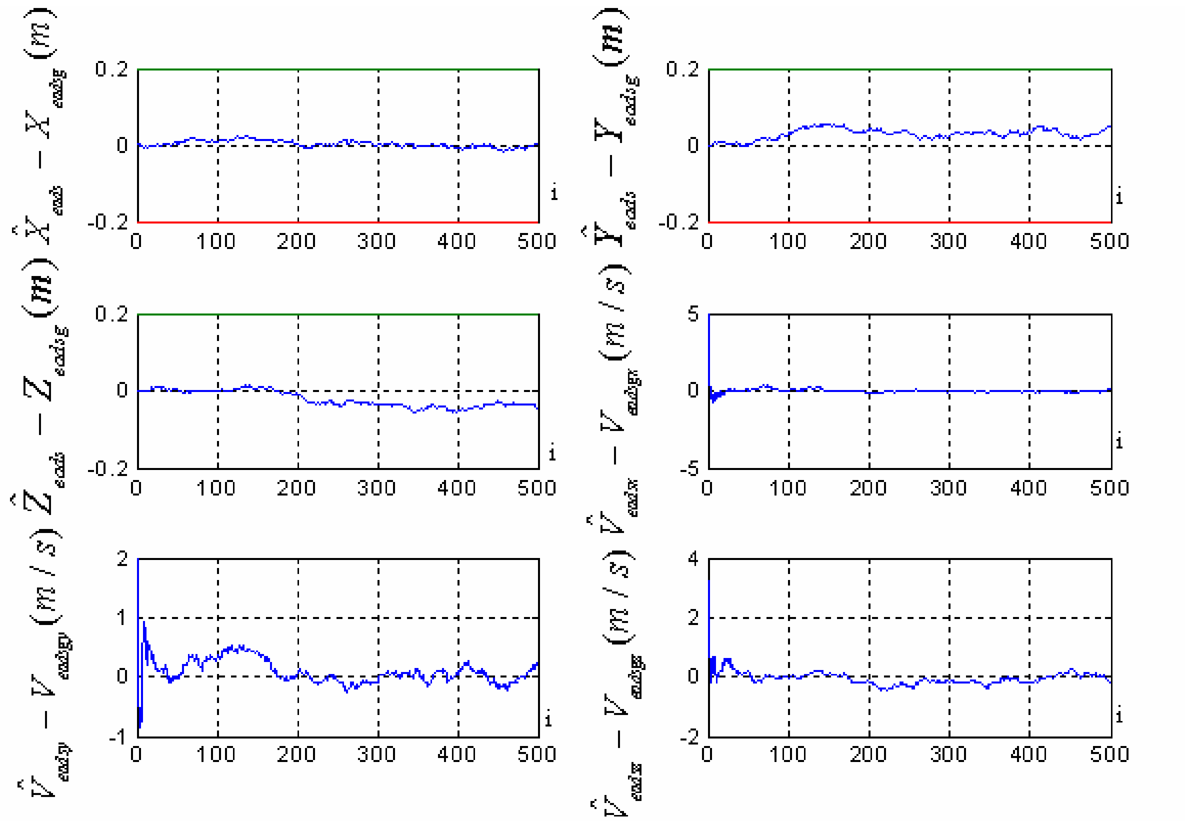

Figure C.7: Differences between estimated and true errors of position and speed

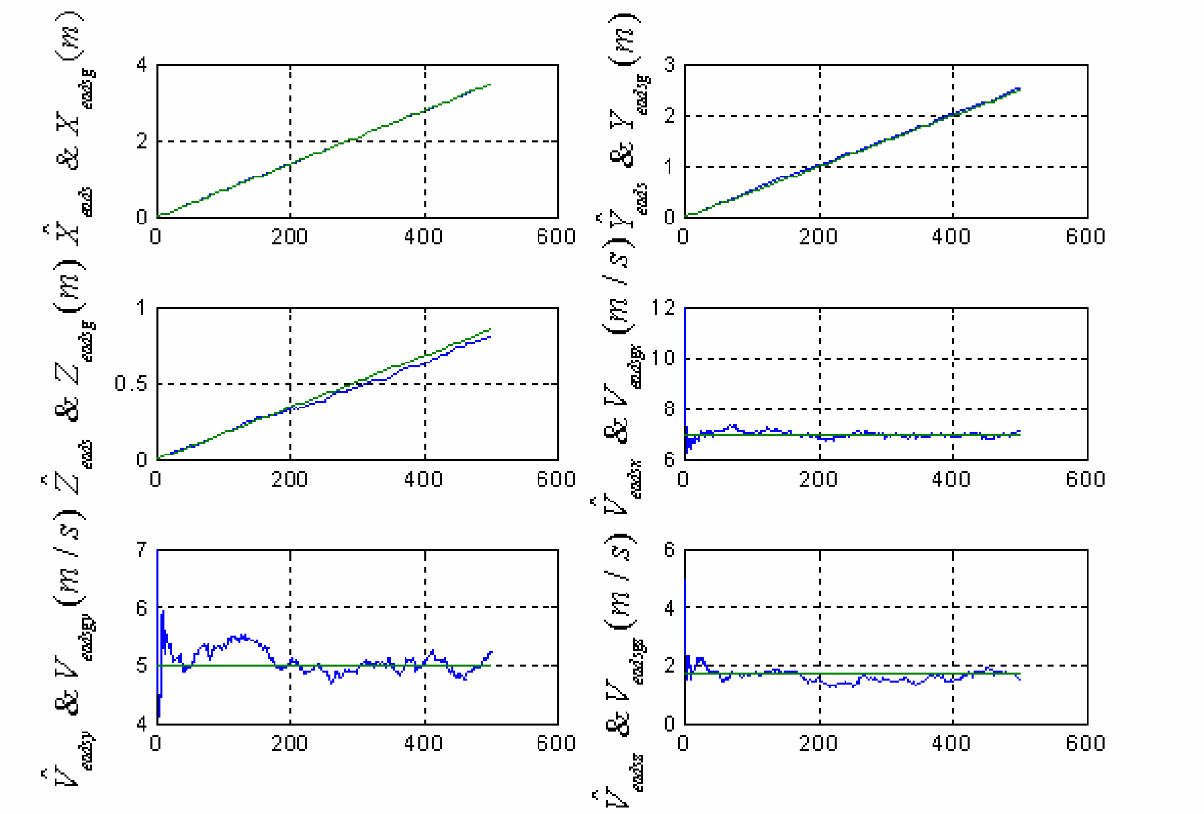

Figure C.8: Estimated and true errors of position and speed

APPENDIX D

KALMAN FILTER BASED INTEGRATION OF ADS AND GPS WHEN BOTH POSITION AND SPEED INCLUDED

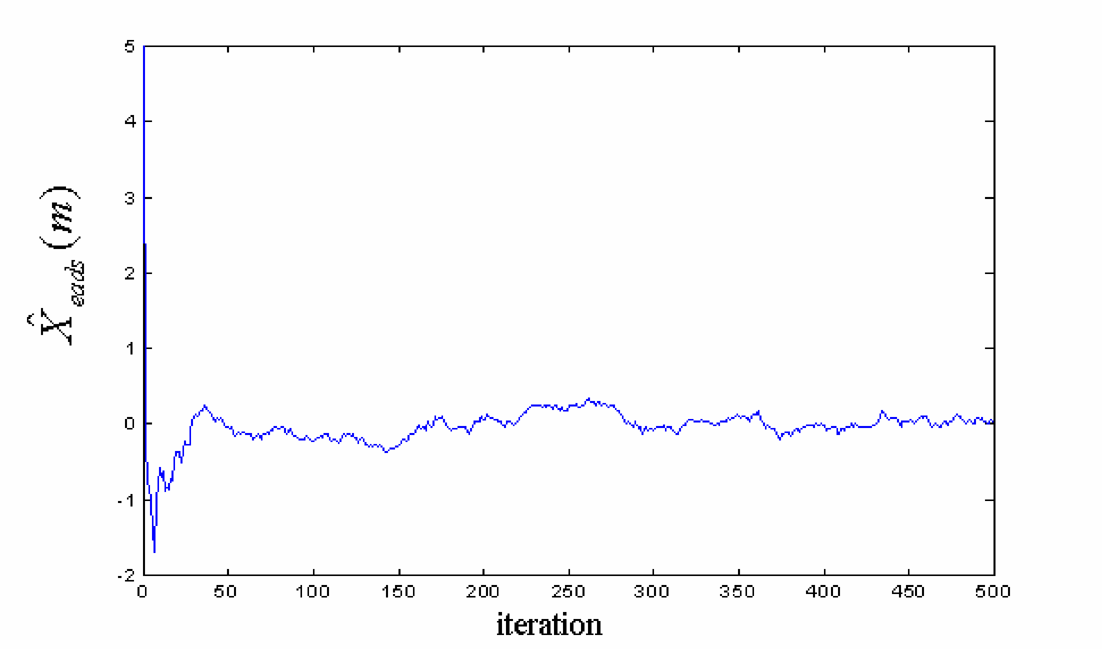

Figure D.1 Error estimate of ADS airspeed in X direction

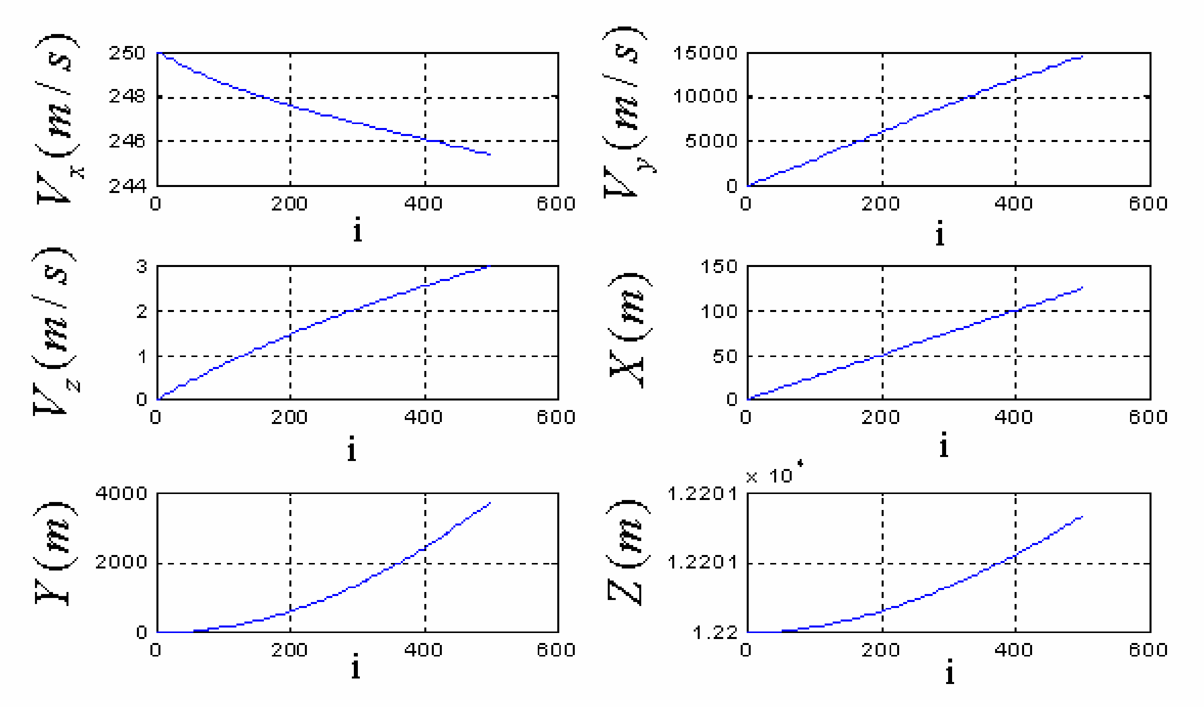

Figure D.2: Position and speed simulations

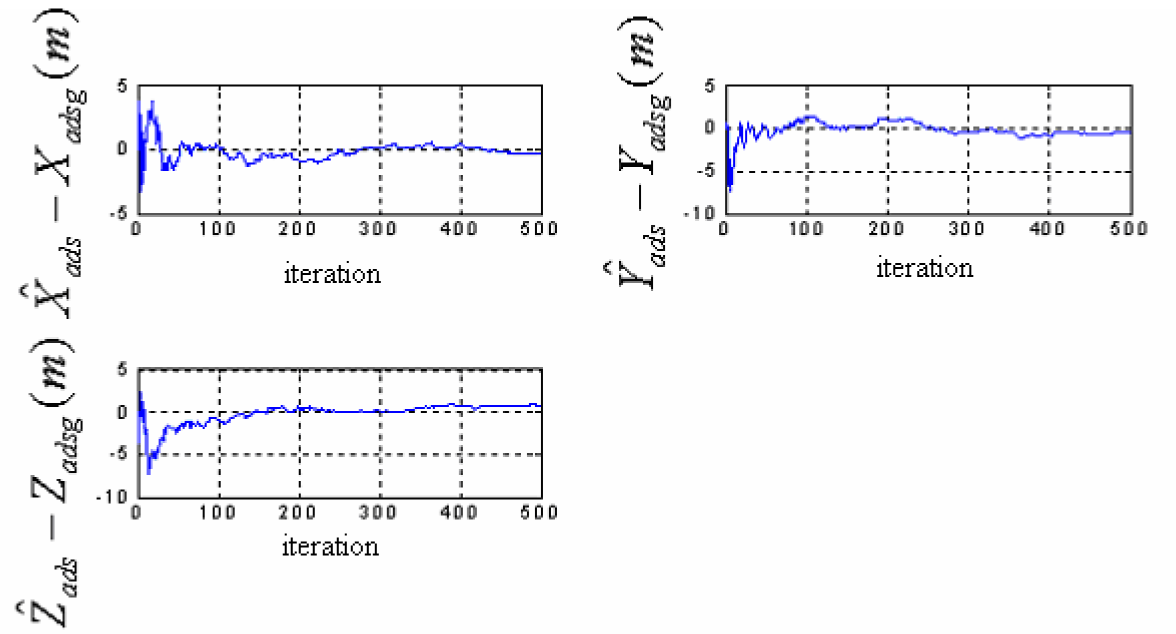

Figure D.3: Position errors in directions X, Y, Z

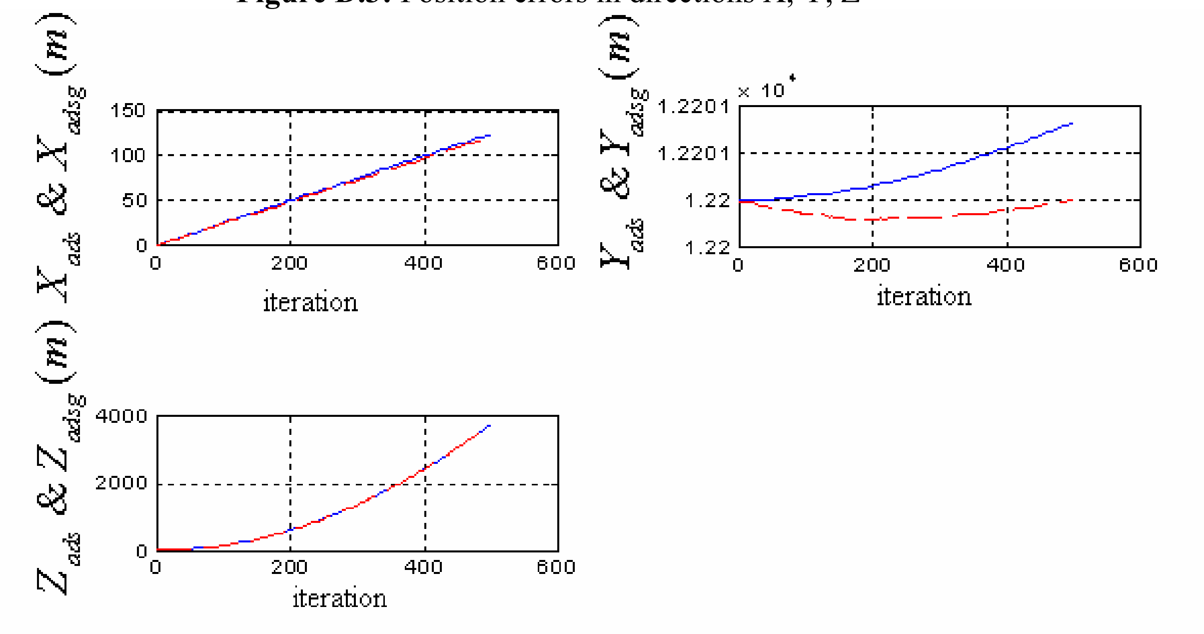

Figure D.4: Simulated position values(solid line) and true position values(dashed line) of ADS

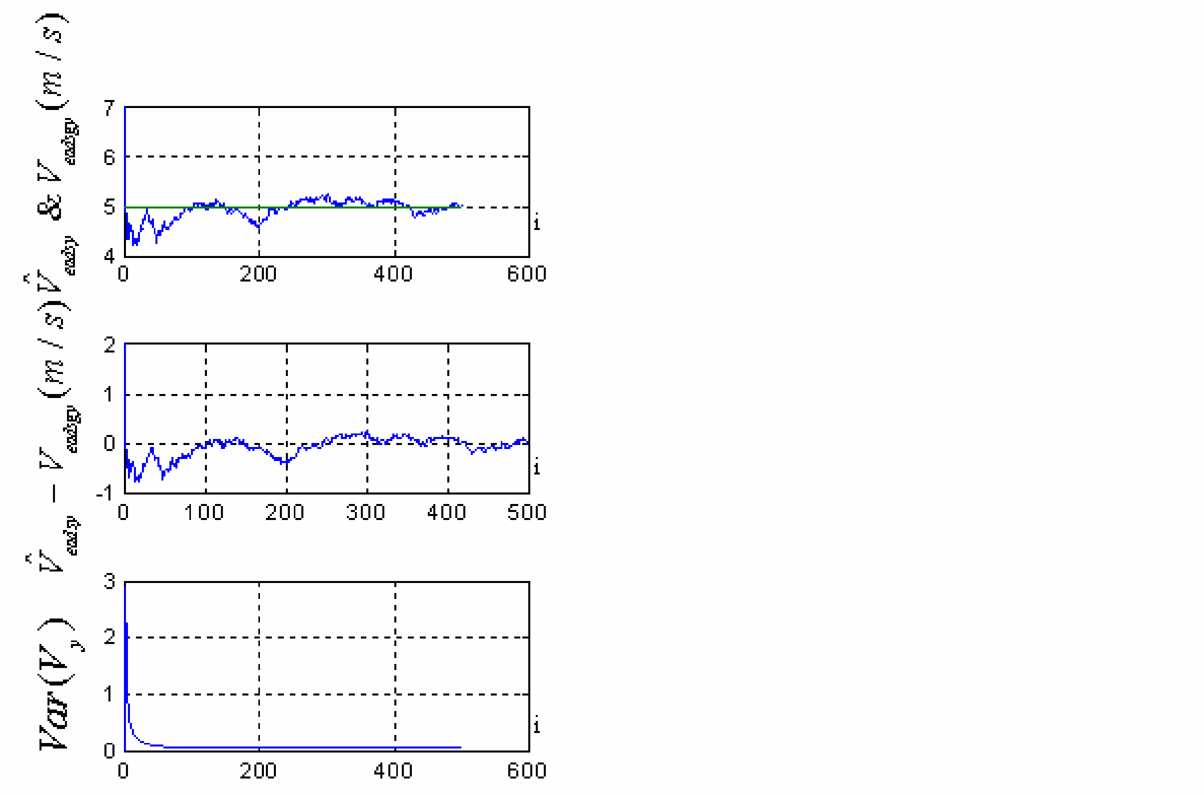

Figure D.5: Y speed KF error and true error and P(k/k) 5th diagonal

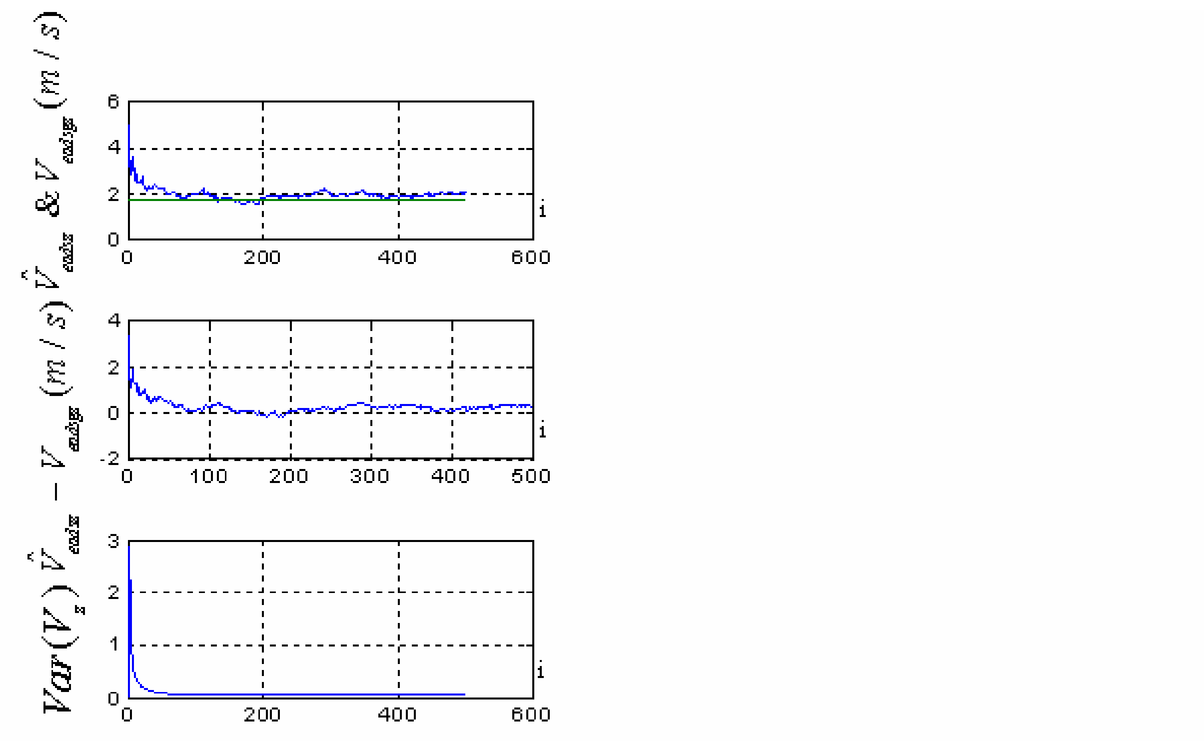

Figure D.6: Z speed KF error and real error and P(k/k) 5th diagonal

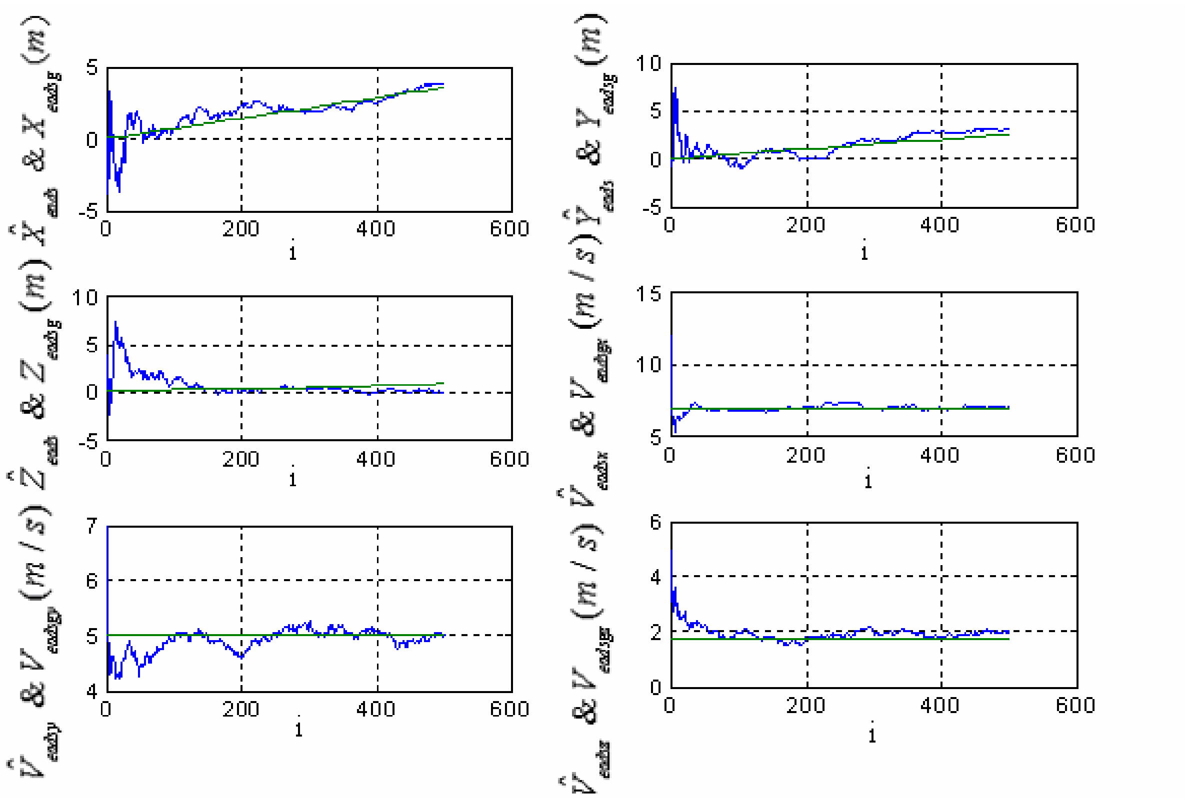

Figure D.7: Estimated and true errors of position and speed

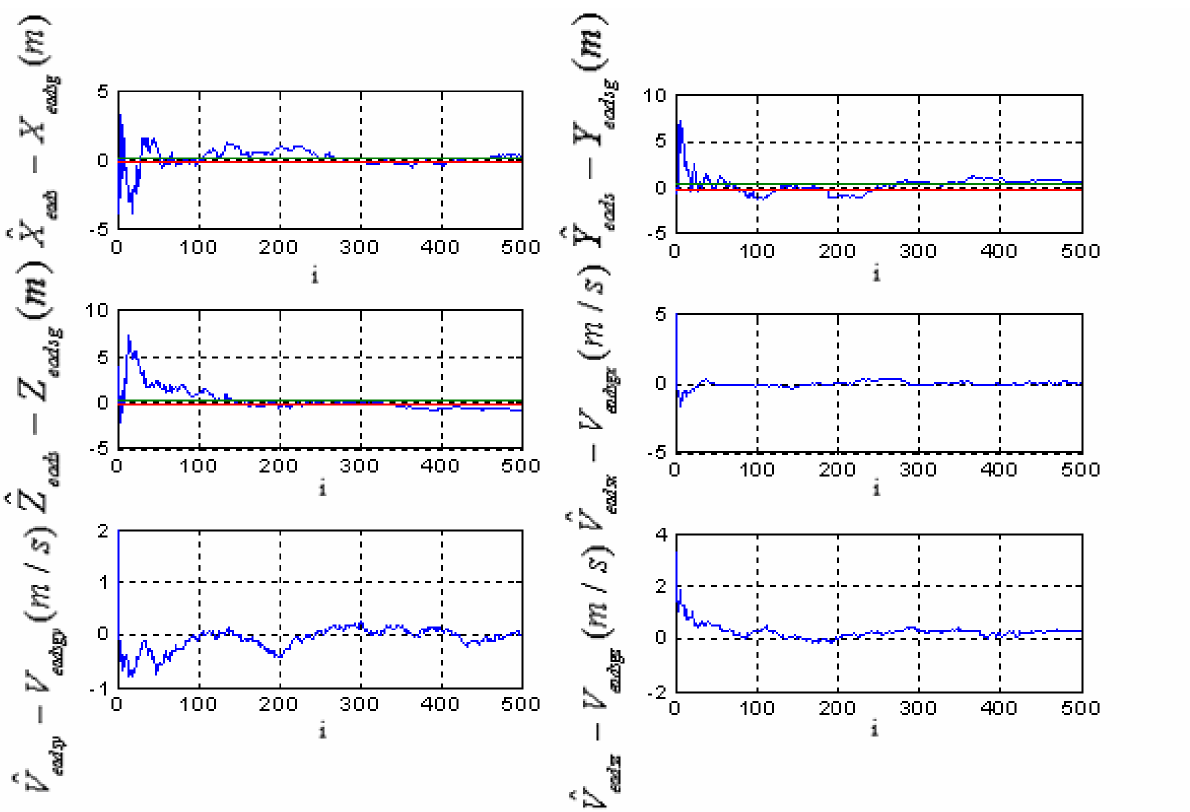

Figure D.8: Differences between estimated errors and true errors of position and speed

ÖZGEÇMİŞ

Yazar Taner MUTLU 1980 yılında Kırcali' de doğmuştur. Ortaöğrenimini Tekirdağ Anadolu Lisesi, lise öğrenimini Kocaeli Körfez Fen Lisesinde tamamladıktan sonra 1999 yılında İstanbul Üniversitesi Elektronik Mühendisliği bölümünde öğrenim hayatına devam etmiştir. 2000 yazını öğrenci değişim programı çerçevesinde ABD de çalışarak geçirmiştir. Çalışma hayatına 2003 yılında GLOBAL Bilgisayar ve Kontrol Sistemleri isimli firmada AR-GE mühendisi olarak başlamıştır.Devre tasarım ve yazılım geliştirme projelerinde yer almıştır. 2004 yılında İTÜ Fen Bilimleri Enstitüsüne Yüksek Lisans öğrencisi olarak girmiştir. 2006 yılı başından itibaren İTÜ-ROTAM' da aviyonik grubunda mühendis olarak çalışmaktadır.